



# First Results from RHIC

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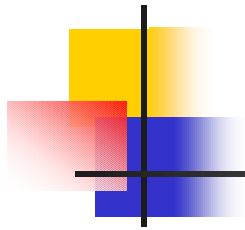
Richard Seto  
University of CA, Riverside  
Caltech, Feb 26, 2001



# Outline

**Note – MANY topics skipped – HBT, particle yields, fluctuations...**

- Introduction to the QCD phase transition, heavy ion collisions
  - The machine and detectors
  - Centrality measurements
    - Changing the size of the collision volume
      - Number of participant nucleons
      - Number of Binary collisions
  - Global Measurements
    - Energy density
    - Thermalization and flow
  - The ideas - Jet quenching, what do we expect?
  - The data - High pt spectra
    - Jet quenching
    - evidence of deconfinement?
  - The future
- Caveats
    - In the interest of clarity I have attempted to tell a story – however please remember
    - The **data is still preliminary** – Generally the systematic errors are estimated to be 30%.
    - In the energy regime we are exploring pQCD becomes a reliable tool – however there are ancillary issues such as the time evolution of the system which are uncertain
    - In the Long Range Plan we are still using words like “preliminary” as opposed to “conclusive”



# Why do this stuff?

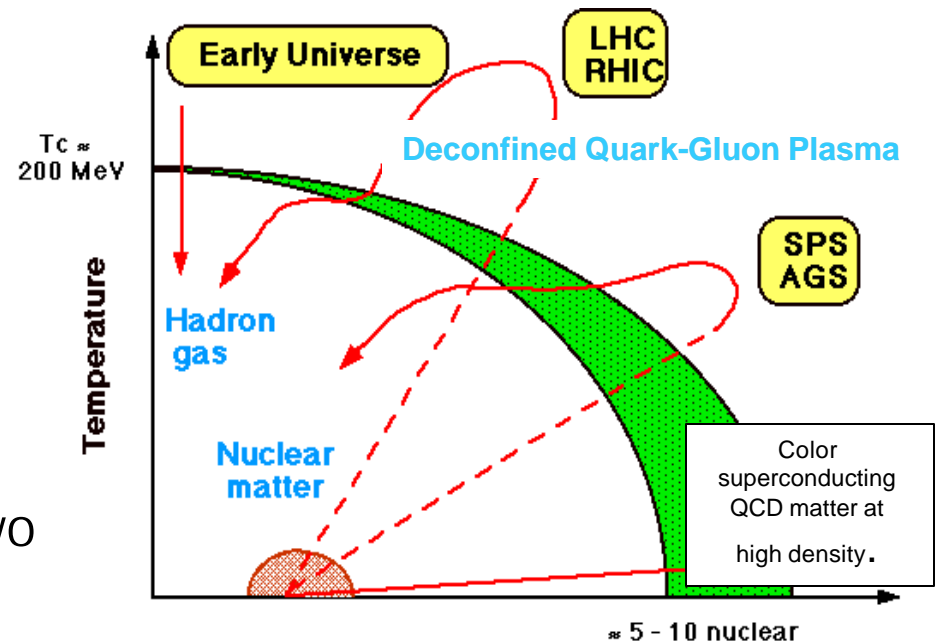
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- Why Relativistic Heavy Ion Collisions?
  - To study a hadronic matter at high energy density
    - Early universe
    - Center of stars
  - To study the deconfined state of QCD
    - Where is the phase transition?
    - What order is it?
    - Are there collective effects ( e.g dis-oriented chiral condensates?
  - To Study the Vacuum - chiral symmetry restoration
    - Origin of (hadronic) mass
- To understand the spin of the proton (polarized pp)

# The QCD phase diagram

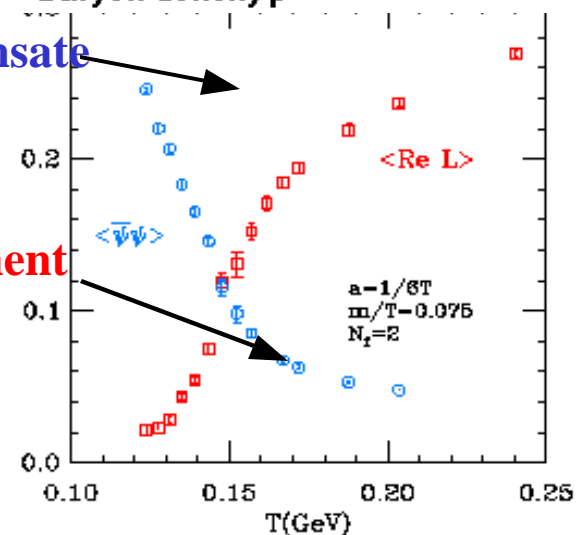
- TWO different phase transitions!
  - The **deconfinement** transition - particles are roam freely over large volume
  - The **chiral** transition - masses change
  - All indications are that these two are at or are very nearly at the same
- Two sets of conditions
  - High Temperature
  - High Baryon Density  $\rho_B$
- Lattice QCD Calculations give  $T_C \sim 150\text{-}170\text{ MeV}$ ;  
 $\mu_{\text{critical}} \sim 0.5\text{-}0.7\text{ GeV/fm}$ 
  - **Two flavor QCD**

T. Blum et al, PRD51(1995) 5153



**Chiral condensate**

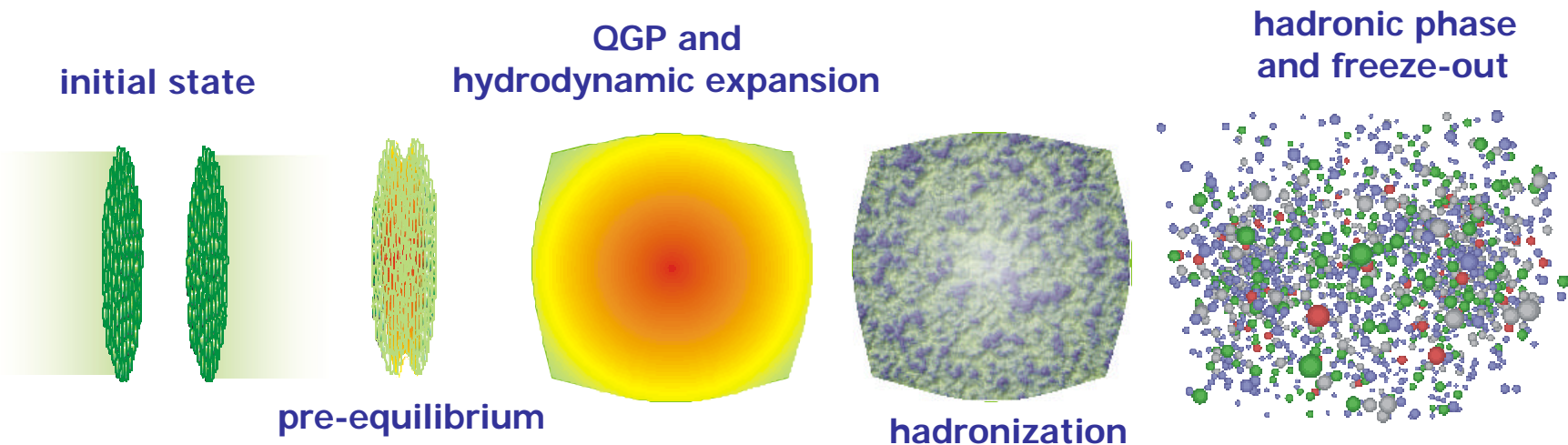
**De-confinement**



# How do we hope to see this phase transition?

- Relativistic Heavy Ion Collisions

- We would like a bottle of compressed quark and gluon gas – but it isn't
- Better analogy – early universe, exploding star
- Time evolution
  - Lorenz contracted pancakes
  - Pre-equilibrium  $\tau \sim 1 \text{ fm}/c$  ??
  - QGP and hydrodynamic expansion  $\tau \sim \text{few fm}/c$  ??
  - Hadronization and freezeout  $\tau \sim 5\text{-}20 \text{ fm}/c$  ??

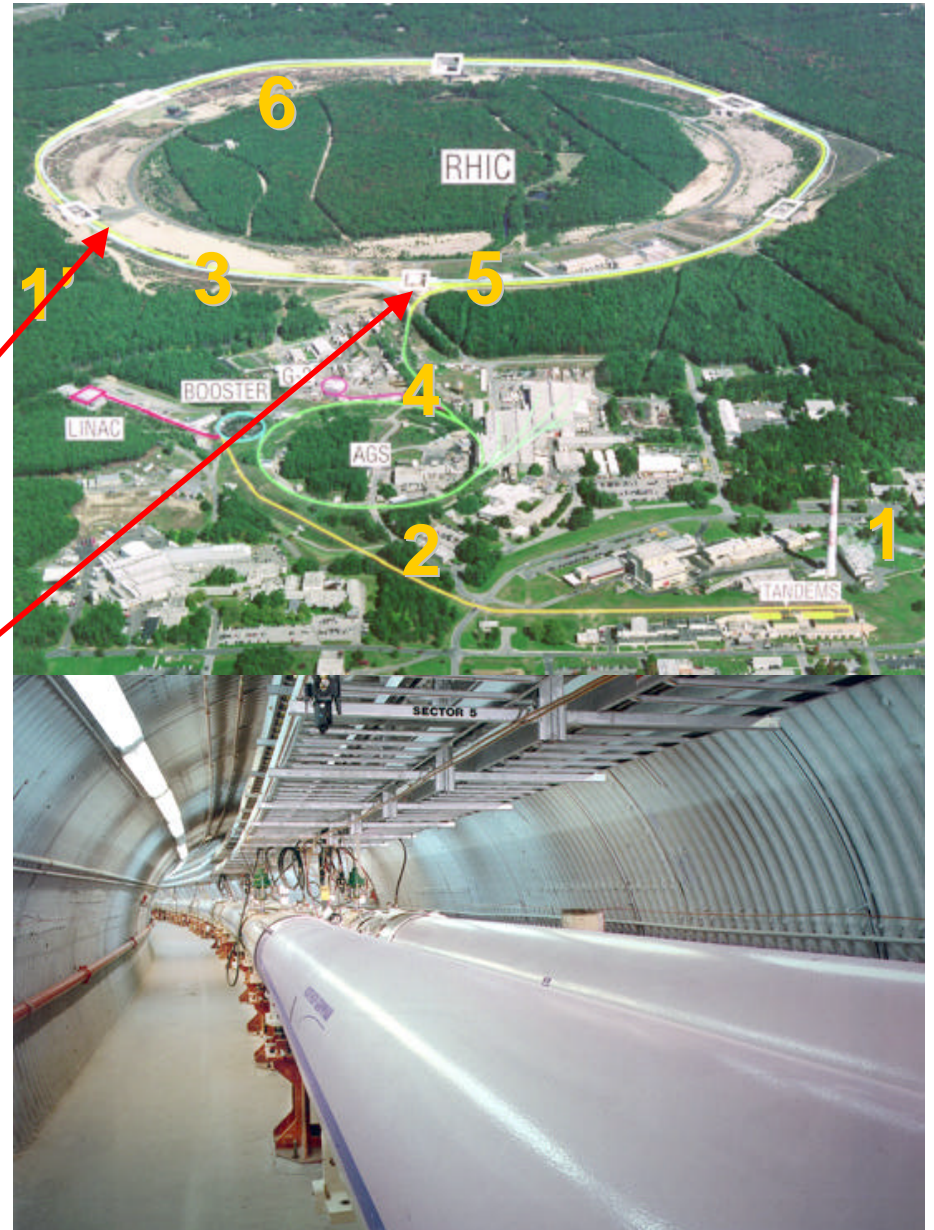


Time Evolution

Richard Seto

# RHIC The Relativistic Heavy Ion Collider

- Located at Brookhaven National Laboratory, Long Island
- Schedule:
  - Commissioning: June-July, 1999
  - First physics run: ~May-00 through Sep-00
- Two independent rings - 4km circumference
- Capable of colliding pp, pA, AA (Au-Au)
- Energy:
  - ➡ 500 GeV for p-p (polarized)  
 $L \sim 2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
  - ➡ 200 GeV for Au-Au  
 $L \sim 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Two Big Detectors
  - PHENIX, STAR
- Two Small Detectors
  - PHOBOS, BRAHMS



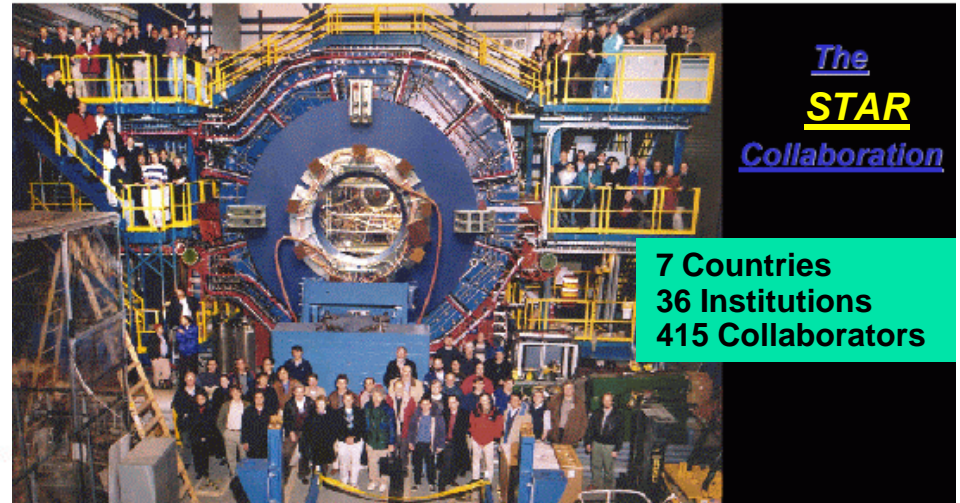


**11 Countries**  
**51 Institutions**  
**~450 Collaborators**



University of São Paulo, São Paulo, Brazil  
Academia Sinica, Taipei 11526, China  
China Institute of Atomic Energy (CIAE), Beijing, P. R. China  
Laboratoire de Physique Corpusculaire (LPC), Université de Clermont-Ferrand, 63170 Aubière, Clermont-Ferrand, France  
CEA, Saclay, Bat. 703, F-91191, Gif-sur-Yvette, France  
IPN-Orsay, Université Paris Sud, CNRS-IN2P3, BP. 1 - F-91406, Orsay, France  
LPNHE-Palaisau, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France  
SOARAT-EC, Ecole des Mines at Nantes, F-44037 Nantes, France  
University of Manchester, Manchester, M13 9PL, UK  
Banaru Hindu University/Banaru, India  
Bhabha Atomic Research Centre (BARC), Bombay, India  
Weizmann Institute, Rehovot, Israel  
Center for Nuclear Study (CNS-Tokyo), University of Tokyo, Tanashi, Tokyo 180, Japan  
Hitachi Energy, Hitachi, Ibaraki 310, Japan  
KEK, Institute for High Energy Physics, Tsukuba, Japan  
Kyoto University, Kyoto, Japan  
Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki, Japan  
RIKEN, Institute for Physical and Chemical Research, Wako, Japan  
University of Tokyo, Bunkyo-ku, Tokyo 113, Japan  
Tokyo Institute of Technology, Goshogawara, Maguro, Tokyo, Japan  
University of Tsukuba, Tsukuba, Japan  
Waseda University, Tokyo, Japan

Cyclotron Applied Laboratory, KAERI, Seod, South Korea  
Kangnung National University, Kangnung 210-720, South Korea  
Korea University, Seoul, 136-701, Korea  
Myong Ji University, Yangju City 449-728, Korea  
System Electronics Laboratory, Seoul National University, Seoul, South Korea  
Yonsei University, Seoul 120-749, Korea  
Institute of High Energy Physics (IHEP-Protvino or Serpukhov), Protvino, Russia  
Joint Institute for Nuclear Research (JINR-Dubna), Dubna, Russia  
Kurchatov Institute, Moscow, Russia  
PNP: St. Petersburg Nuclear Physics Institute, Gatchina, Leningrad, Russia  
Lund University, Lund, Sweden  
Ahlborn Electronic GmbH, Garmisch, Germany  
Ahlborn Electronics Inc., Dallas, Texas, USA  
Brookhaven National Laboratory (BNL), Upton, NY 11973  
University of California - Riverside (UCR), Riverside, CA 92521, USA  
Columbia University, Nevis Laboratories, Irvington, NY 10533, USA  
Florida State University (FSU), Tallahassee, FL 32306, USA  
Georgia State University (GSU), Atlanta, GA 30303, USA  
Iowa State University (ISU) and Ames Laboratory, Ames, IA 50011, USA  
LNL: Los Alamos National Laboratory, Los Alamos, NM 87545, USA  
LNL: Lawrence Livermore National Laboratory, Livermore, CA 94550, USA  
University of New Mexico, Albuquerque, New Mexico, USA  
New Mexico State University, Las Cruces, New Mexico, USA  
Department of Chemistry, State University of New York at Stony Brook (SUNY),  
Stony Brook, NY 11794, USA



**7 Countries**  
**36 Institutions**  
**415 Collaborators**

Brazil:	Sao Paolo	China:	IHEP - Beijing, IPP - Wuhan
England:	Birmingham	France:	IReS - Strasbourg, SUBATECH-Nantes
Germany:	Frankfurt, MPI - Munich	Poland:	Warsaw University, Warsaw U. of Technology
		Russia:	MEPHI - Moscow, JINR - Dubna, IHEP - Protvino
U.S.:	Argonne, Berkeley, Brookhaven National Laboratories UC Berkeley, UC Davis, UCLA, Creighton, Carnegie-Mellon, Indiana, Kent State, MSU, CCNY,		

## BRAHMS Collaboration

## Smaller experiments

~ \$5M

## ~50 Collaborators

Brookhaven National Laboratory, USA  
Fysisk Institut, University of Oslo Norway  
IRES, Université Louis Pasteur, Strasbourg, France  
Jagellonian University, Cracow, Poland  
Johns Hopkins University, Baltimore, USA  
New York University, USA  
Niels Bohr Institute, University of Copenhagen, Denmark  
Texas A&M University, College Station, USA  
University of Bucharest, Romania  
University of Kansas, USA  
University of Bergen, Norway


I.G. Baerén\*, D. Beuvin\*, Y. Blyakhnik\*, J. Broeckhove\*, E. Budini\*, H. Eggeli\*, C. Charman\*, P. Christmann\*, J. Côté\*,  
F. Delbo\*, J. J. Gaardhøi\*, K. Grotzinger\*, J. Jorde\*, F. Joud\*, K. Kage\*, O. Hansen\*, H. Hagedorn\*, A. Holm\*,  
G. Holm\*, A.K. Hahn\*, H. Ho\*, E. Jacobsen\*, A. Jipa\*, C. E. Jørgensen\*, E. J. Kim\*, T. Knecht\*,  
Konk\*, J.M. Larsen\*, J. H. Lee\*, Y. K. Lee\*, O. Levstik\*, Z. Majar\*, A. Mikhov\*, B. McInnes\*, M. Murny\*, J.  
Natorcz\*, B.S. Nielsen\*, K. Okkenhaug\*, D. Owsian\*, R. Plesch\*, F. Ramf\*, D. Rosnick\*, B. Samset\*, S.  
Sandvik\*, R.A. Schaefer\*, I. S. Sørensen\*, Z. Sojka\*, P. Staszko\*, T. S. Tveit\*, F. Vukobrat\*, R. Wade\* and A. Wistich

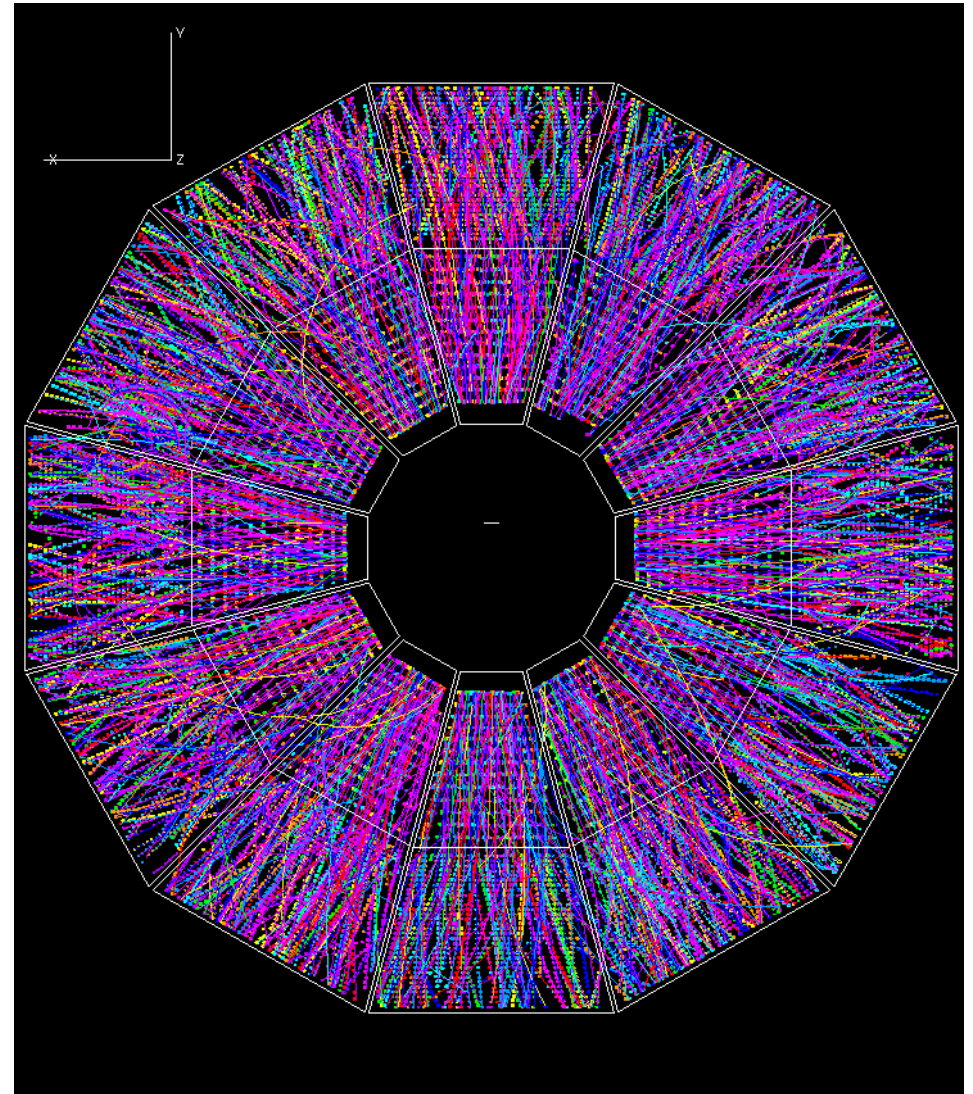
The **PHOBOS** Collaboration

**ARGONNE NATIONAL LABORATORY**  
Elmer Bark, Nigel George, Alan Wuosmaa  
**BERNSTEIN NATIONAL LABORATORY**  
Mark Baker, Donald Barton, Alan Carroll, Stephen Gauthier, George Heitzmann, Robert Pak, Louis Rosenberg, Peter Steinberg, Andrei Sudhanov  
**INSTITUTE OF NUCLEAR PHYSICS, KRAKOW**  
Andrzej Dudziszewski, Roman Holynski, Jozef Michalowski, Andrzej Olizakowski, Pawel Sosnicki, Marek Stokich, Adam Trzaskiel, Barbara Wosiek, Krzysztof Wozniak  
**MASSACHUSETTS INSTITUTE OF TECHNOLOGY**  
**Wt Busca\***, Piotr Decowski, Krzysztof Gultbransen, Corcor Henderson, Jay Kane, Judith Katz, Piotr Kulinski, Johannes Muehlmann, Heinz Pernegger, Corey Reed, Christel Roland, Guilhaume Ruzard, Leslie Ricevour, David Sack, Sam Saxon, George Stephens, Gert van Nieuwenhuizen, Carla Valle, Robin Verdier, Bernard Wadsworth, Dariusz Wyslouch  
**NATIONAL CENTRAL UNIVERSITY, TAIWAN**  
Willie Lin, Jia-Luen Tang  
**UNIVERSITY OF ROCHESTER**  
Josh Hamblen, Erik Johnson, Razim Khan, Steven Raby, Ingu Park, Wojtek Skalski, Ray Tang, Frank Wolfe  
**UNIVERSITY OF ILLINOIS AT CHICAGO**  
Russell Smith, Cive Hallinan, David Hofman, Burt Holzman, Wojtek Kuczewicz, Don McLeod, Rachid Noufir, Michael Rector  
**UNIVERSITY OF MARYLAND**  
Richard Bindel, Eduardo Garcia-Solis, Alice Mignany



# A STAR picture – design considerations

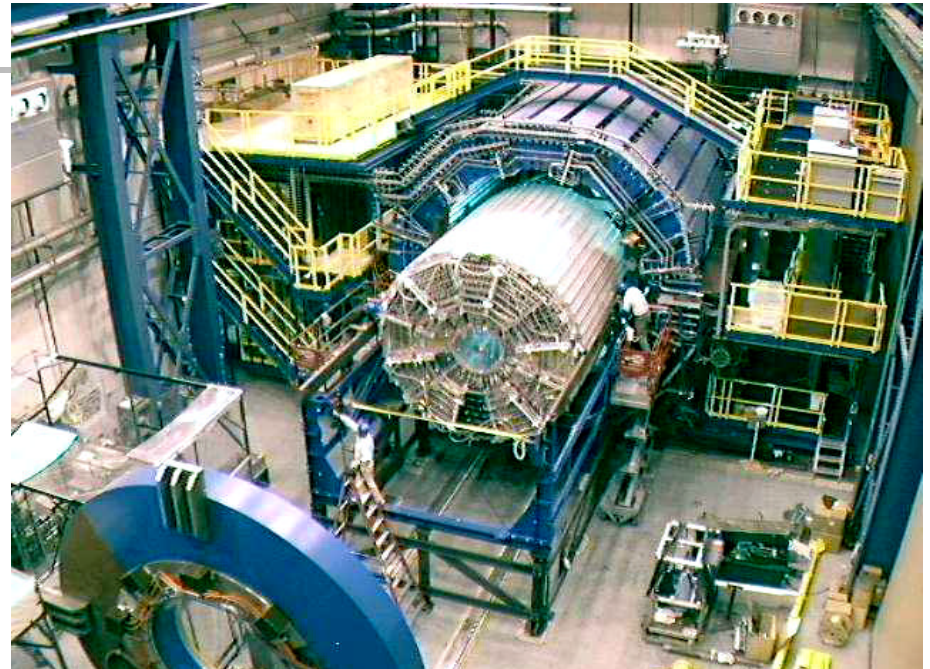
- An early high multiplicity event 
- Design Considerations
  - High granularity
  - Low pt capability
  - High pt capability
  - Good PID
  - Large acceptance
  - Good momentum resolution
  - Cheap
- Can't have it all
  - ➔ Different Philosophies



# The "Large" Detectors

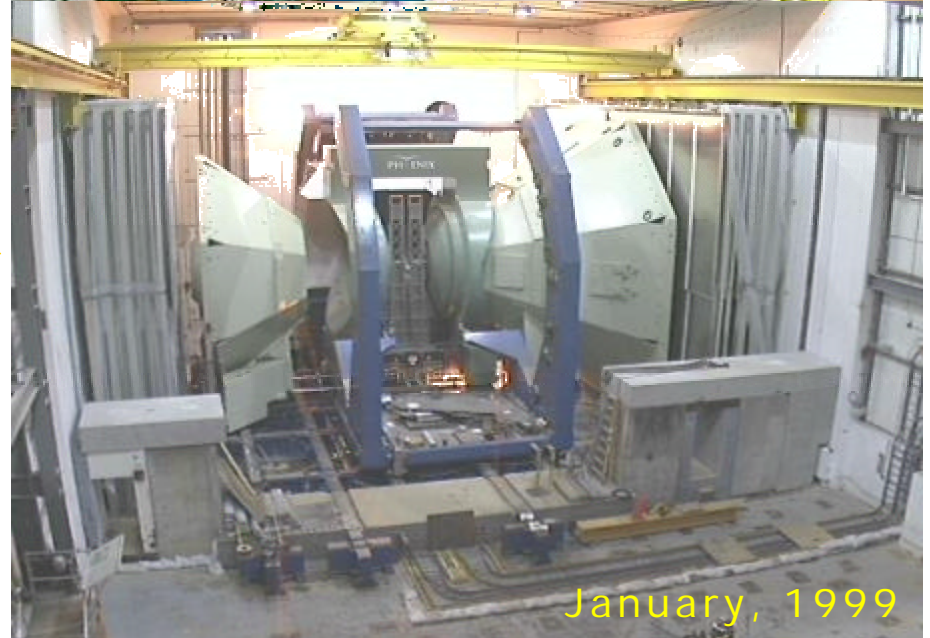
## ■ STAR

- Large acceptance TPC
  - Solenoidal Field
  - $-1 < \eta < 1$
- Vertex Detection - SVT
- Primarily Hadrons - year 1
  - Multi-strange baryons
- EMCAL - 2nd year - photons/electrons



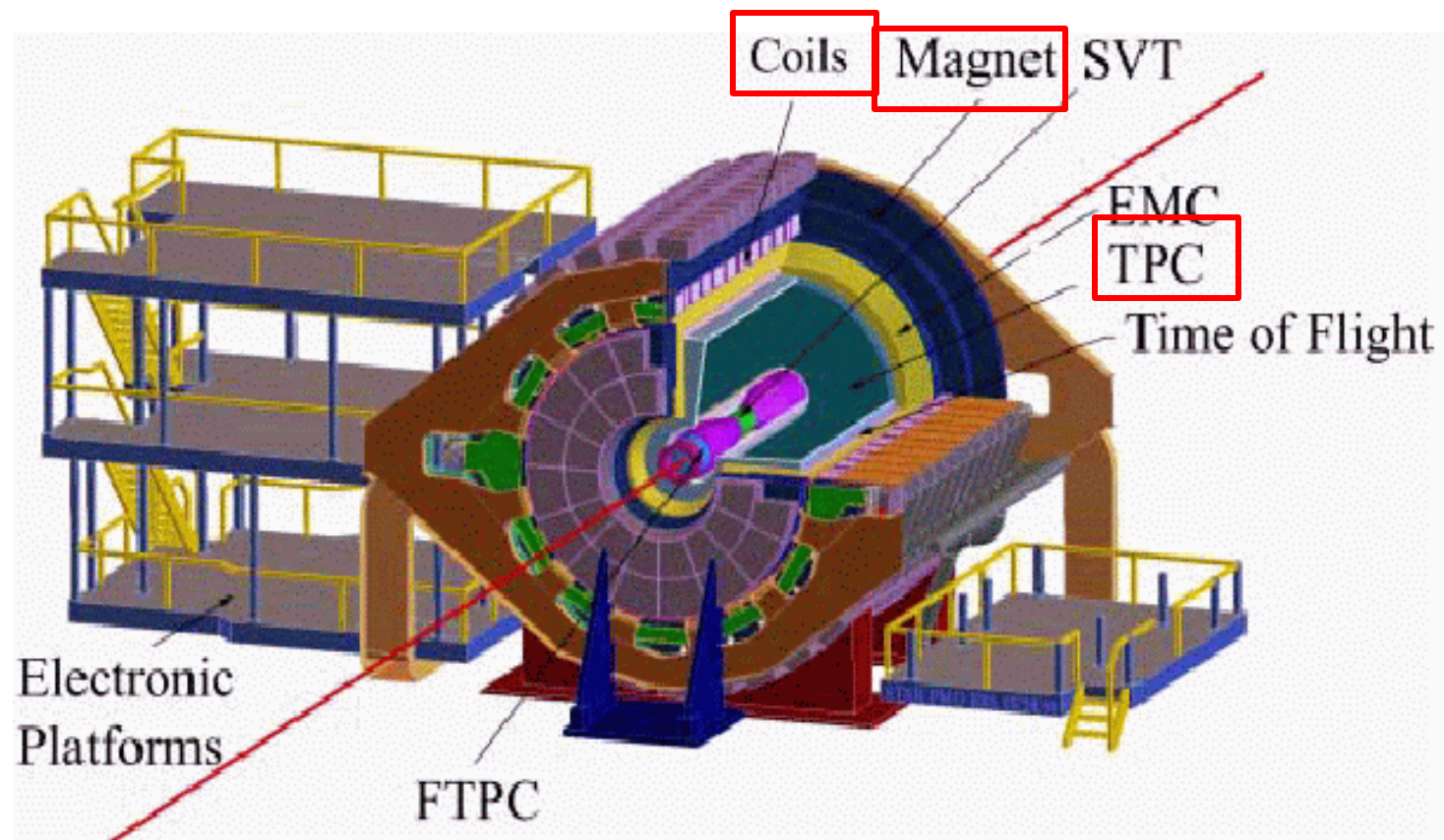
## ■ PHENIX

- an apparatus for **electrons, muons, photons and hadrons**
- 2 Arm central spectrometer + 2 muon endcaps
- Limited acceptance
  - $-0.35 < \eta < 0.35$  (e,  $\gamma$ , hadrons)
  - $1.2 < |\eta| < 2.5$  (muons-2nd year)
- Open Geometry Axial Field (like a Helmholtz coil)
- High rate, good PID, Good momentum resolution



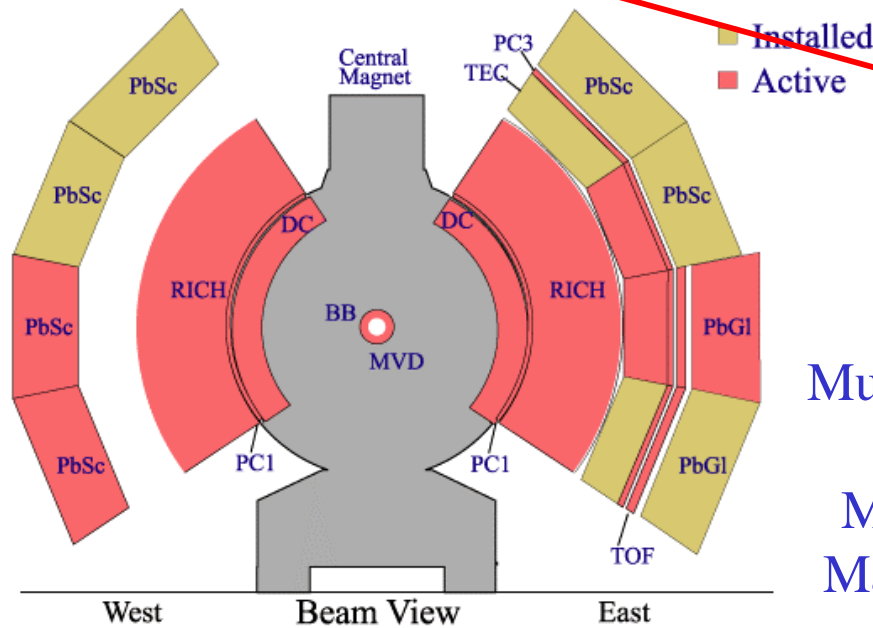
January, 1999

# STAR – year 1

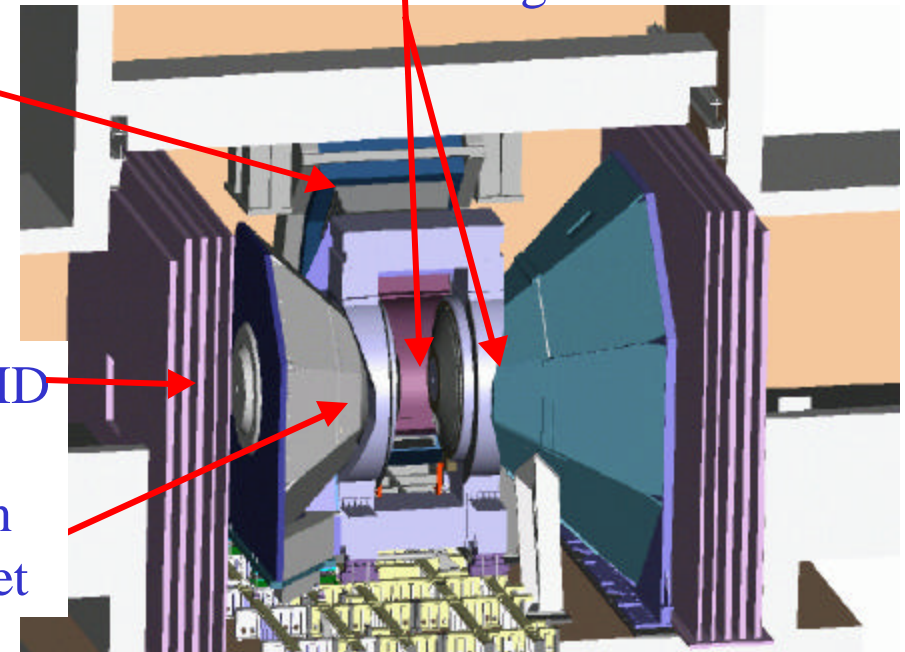


# PHENIX: year 1 configuration

## Central Arms

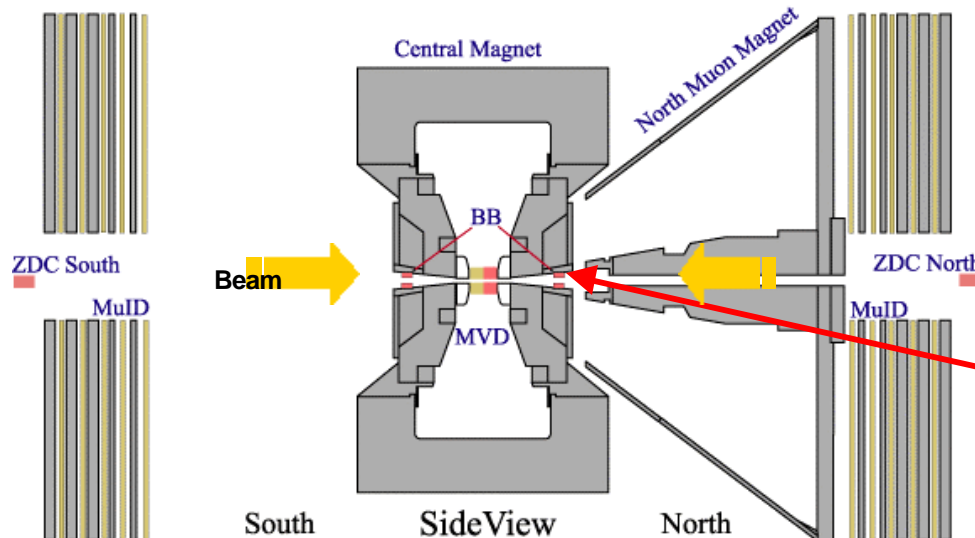


## Central Magnet



Muon ID

Muon Magnet



## Tracking

- DC, PC
- Particle ID
  - EMCal, RICH, TOF, TEC

## Global Detectors (centrality)

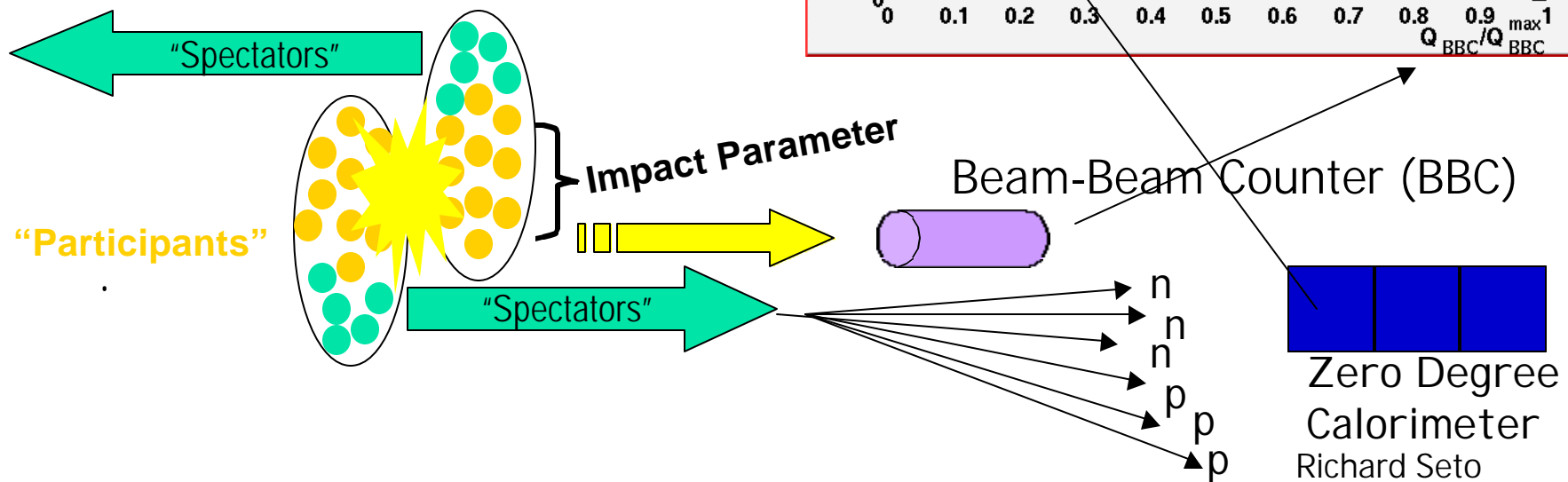
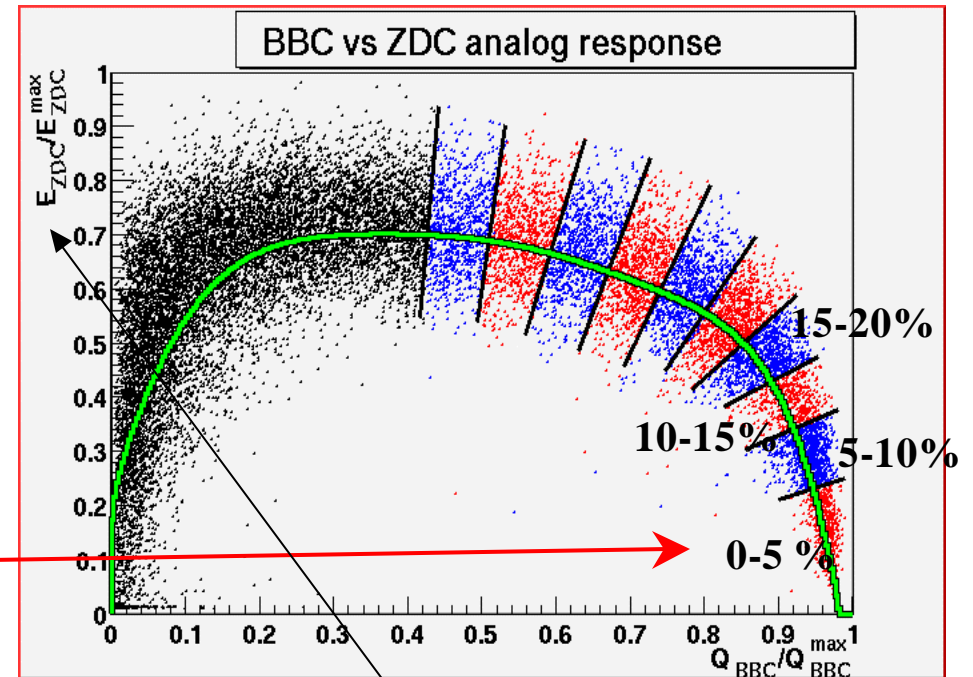
- Zero Degree Calorimeter (ZDC)
- Beam-Beam Counter (BBC)
- MVD (year 2)

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# We need to worry about Geometry

## Measuring Centrality (impact parameter)

- Zero Degree Calorimeters (ZDC) only measure spectator neutrons, since charged particles are swept aside by accelerator magnetic fields.
- These calorimeters are common to all four RHIC C experiments
- Using a combination of the ZDC's and BBC's we can define Centrality Classes



# Conversion from Centrality to $N_{\text{binary}}$ collisions and $N_{\text{participants}}$

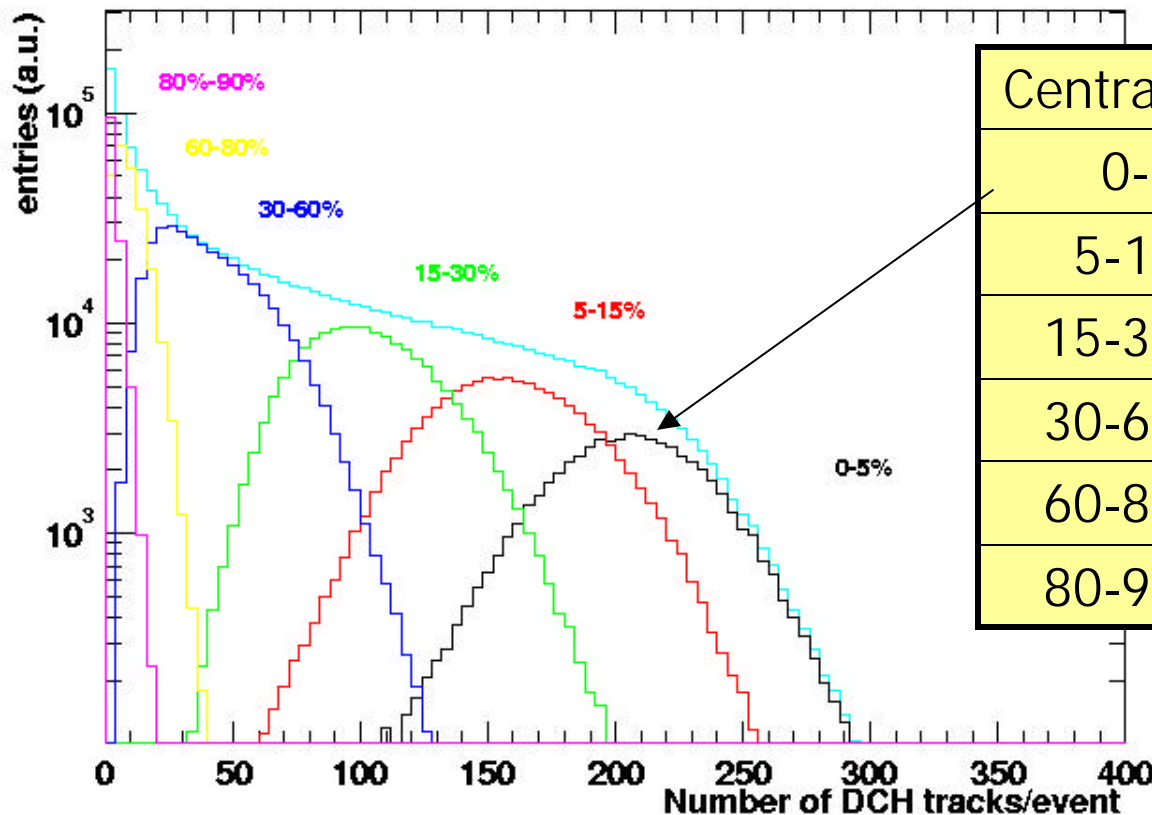
Many models of particle production identify two components.

(A) Soft interactions where production scales with  $N_{\text{participants}}$

(B) Hard interactions where production scales with  $N_{\text{binary}}$

$$dN_{ch}/d\mathbf{h}|_{h=0} = A \times N_{part} + B \times N_{bin}$$

A simple Glauber model gives  $N_{\text{binary}}$  and  $N_{\text{participants}}$



Centrality	Collisions	Participants
0-5%	$945 \pm 15\%$	$347 \pm 15\%$
5-15%	$673 \pm 15\%$	$271 \pm 15\%$
15-30%	$383 \pm 15\%$	$178 \pm 15\%$
30-60%	$123 \pm 15\%$	$76 \pm 15\%$
60-80%	$19 \pm 60\%$	$19 \pm 60\%$
80-92%	$3.7 \pm 60\%$	$5 \pm 60\%$

Introduces systematic error  
Large for peripheral events

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# Initial Conditions

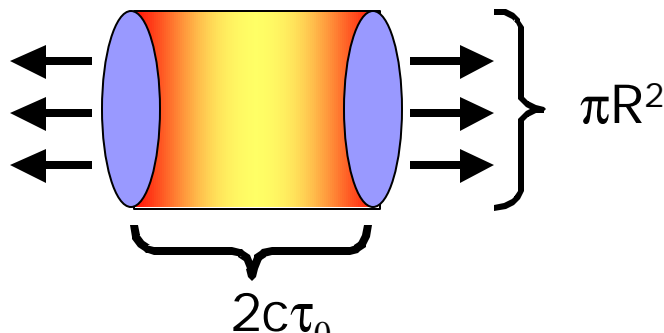
- What is the energy density achieved?
- How does it compare to the expected phase transition value from lattice QCD?
- Is this energy density thermalized?

Bjorken formula for thermalized energy density

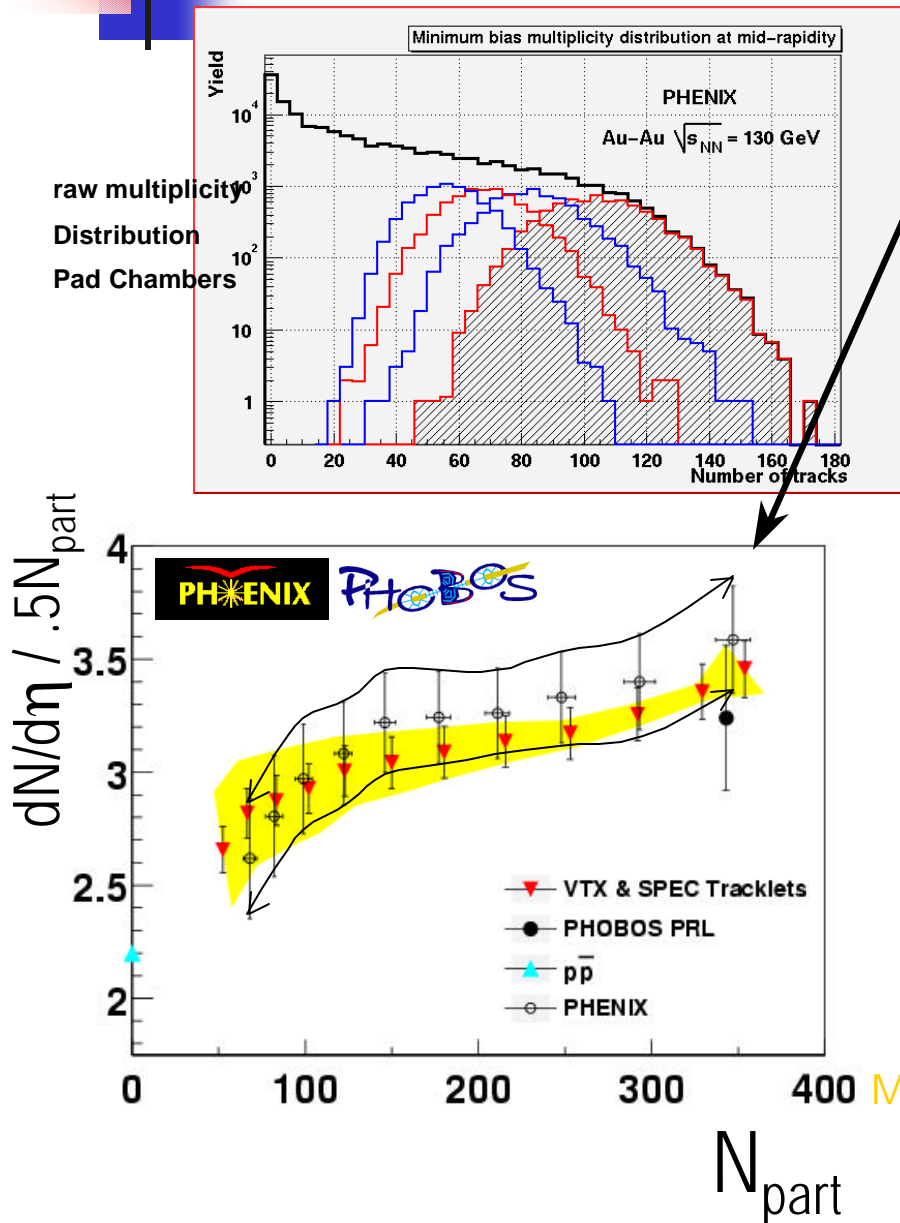
$$e_{Bj} = \frac{1}{pR^2} \frac{1}{2t_0} \frac{dE_T}{dy}$$

Need to measure  
transverse energy  
( $E_T$ )

Need to estimate the  
time to thermalize  
the system ( $\tau_0 \sim 0.5$   
fm/c)



# Multiplicity



- Divide by  $N_{part}$
- Good consistency between experiments
- Yields grow significantly faster than  $N_{participants}$
- Evidence for term  $\sim N_{collisions}$ 
  - Hard processes increase with centrality (30% mid-central to ~50% most central)

$$dN_{ch}/d\eta|_{h=0} = A \times N_{part} + B \times N_{bin}$$

$$A = 0.88 \pm 0.28 \quad B/A = 0.38 \pm 0.19$$

$$B = 0.34 \pm 0.12 \quad \text{PHENIX preliminary}$$

First PHENIX paper submitted !

“Centrality Dependence of Charged Particle Multiplicity in Au-Au Collisions at  $\sqrt{s_{NN}} = 130$  GeV”  
nucl-ex/0012008

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# Transverse Energy

PHENIX Electromagnetic calorimeter measures transverse energy.

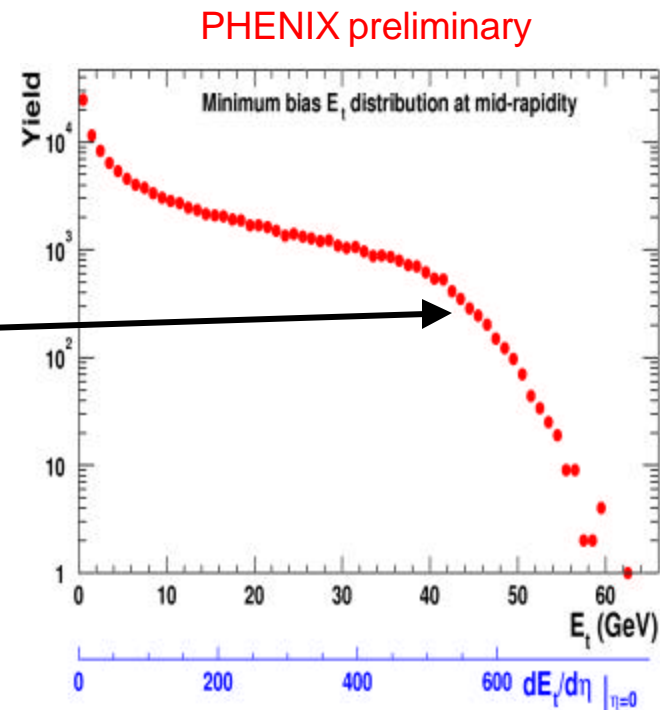
For the most central events:

$$\epsilon_{\text{Bjorken}} \sim 5.0 \text{ GeV/fm}^3$$

Lattice phase transition:

$$\epsilon_{\text{critical}} \sim 0.5\text{-}0.7 \text{ GeV/fm}^3$$

Energy deposition is certainly adequate, but does it create a thermalized new phase of matter?



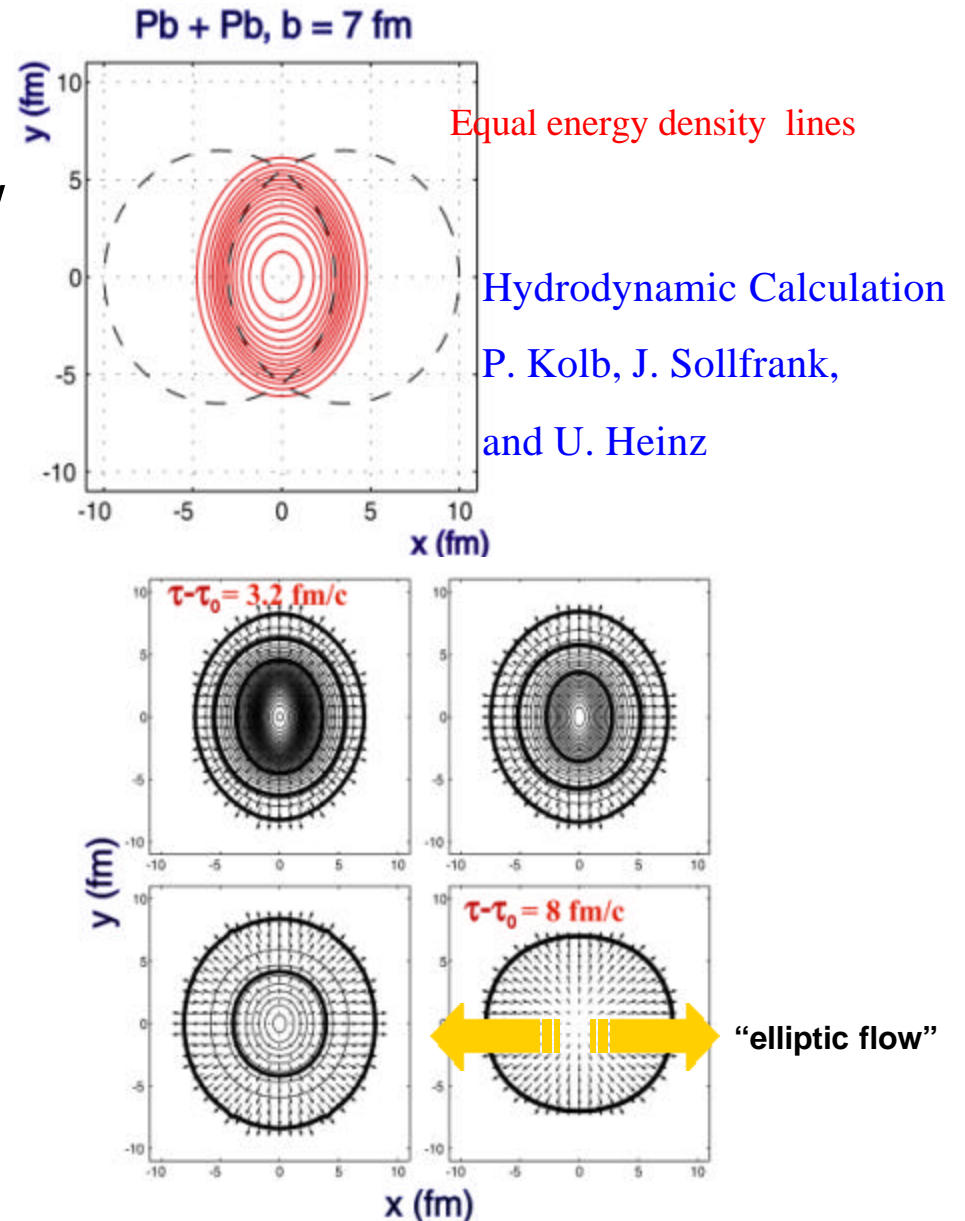
# Is the system thermal? Look at “elliptic flow”

## ■ Flow

- Pressure build up (energy density profile)
- Explosion with azimuthal asymmetry
  - Zero for central collisions

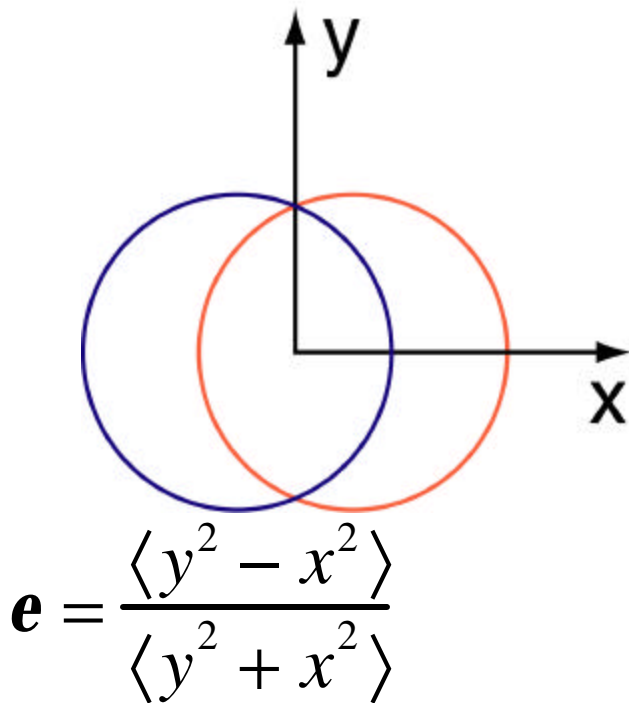
## ■ Hydrodynamics

- Assumes continuum matter with local equilibrium
  - Locally equilibrated or “thermalized”

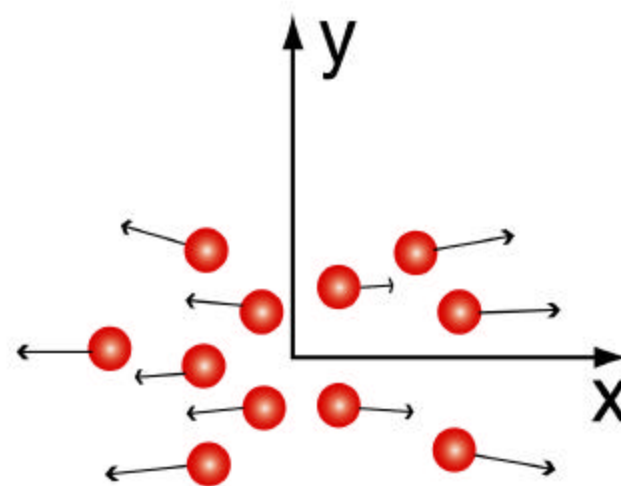


## Definitions - $v_2$ , a measure of elliptic flow

$$dN/dydp_T^2d\mathbf{f} \propto 1 + 2v_2(p_T) \cos(2\mathbf{f})$$



Almond shape overlap region  
in coordinate space



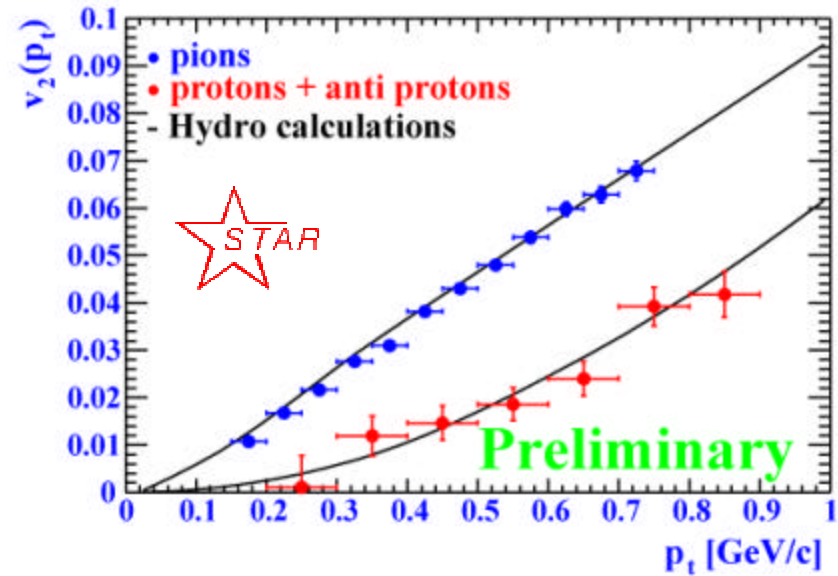
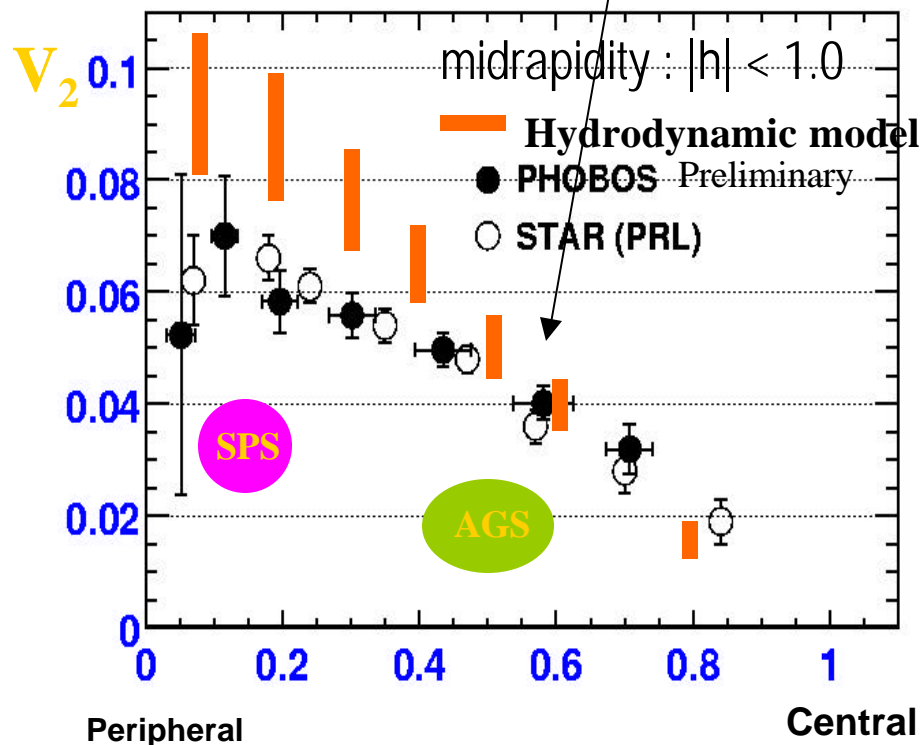
$$v_2 = \langle \cos 2\mathbf{f} \rangle$$

$$\mathbf{f} = \text{atan} \frac{p_y}{p_x}$$

Gives asymmetry in Momentum space

# Centrality, PT Dependence of $v_2$

- Strong flow signal
- Consistent with Hydrodynamics to mid-central



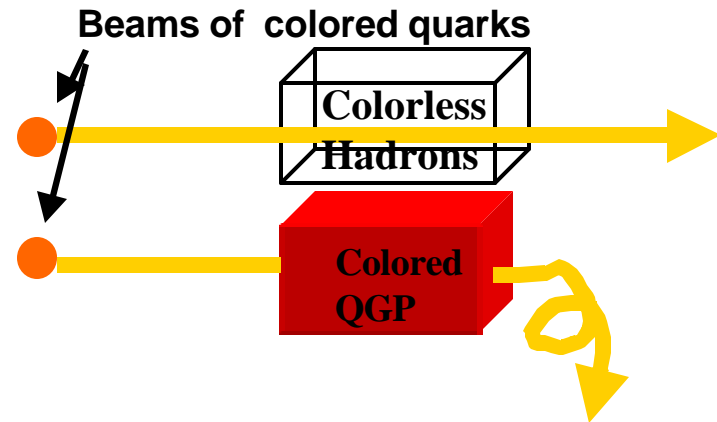
OK, looks like we might have a system of high energy density that is consistent with being reasonably thermalized

Now What?

Answer – Probe the system, Let's see what kind of muck we made!

# Hard Probes In Heavy Ion Collisions, aka Jet quenching

- The experiment we would like to do – Deep Inelastic Scattering of the QGP



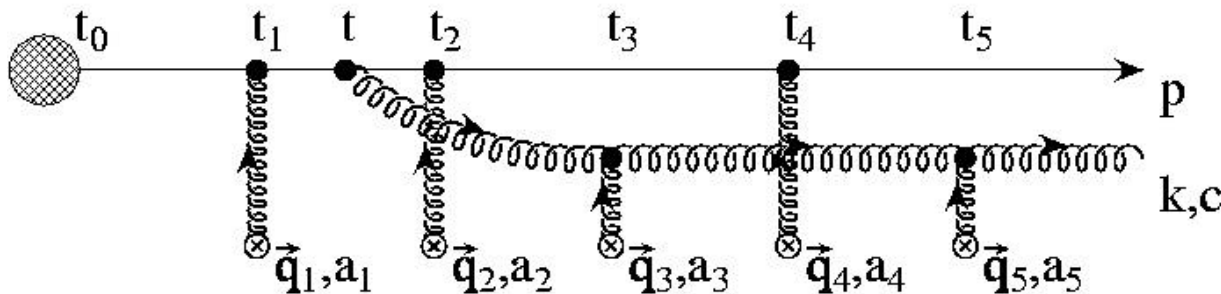
- “hard” probes

- Formed in initial collision with high  $Q^2$ 
  - penetrate hot and dense matter
  - sensitive to state of hot and dense matter
    - $dE/dx$  by strong interaction
    - $\mathbf{P}$  jet quenching

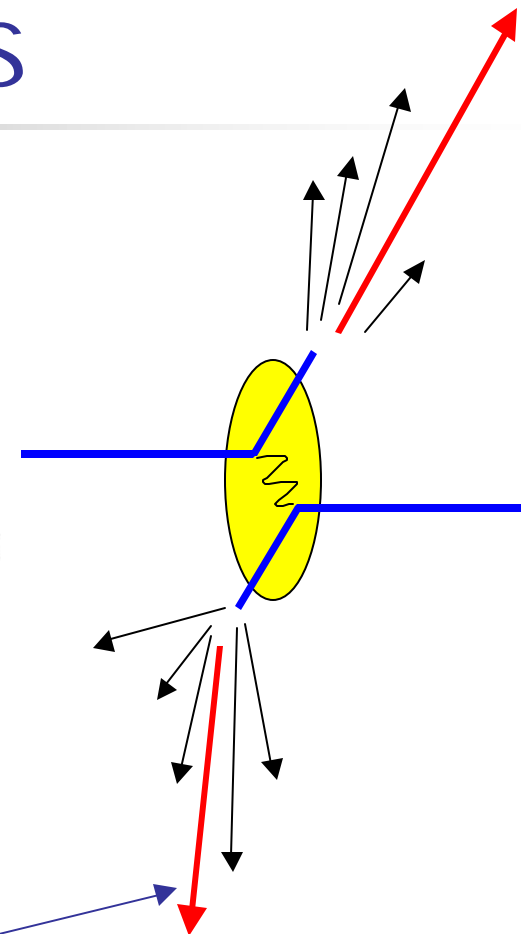


# Parton Energy Loss

- Partons are expected to lose energy via gluon radiation in traversing a quark-gluon plasma



- Two forms of energy loss considered
  - $dE/dx \sim \text{constant}$ , static plasma
  - $dE/dx \sim L$ 
    - This latter one is from QCD calculations (interference)
    - Both Static and expanding plasma considered



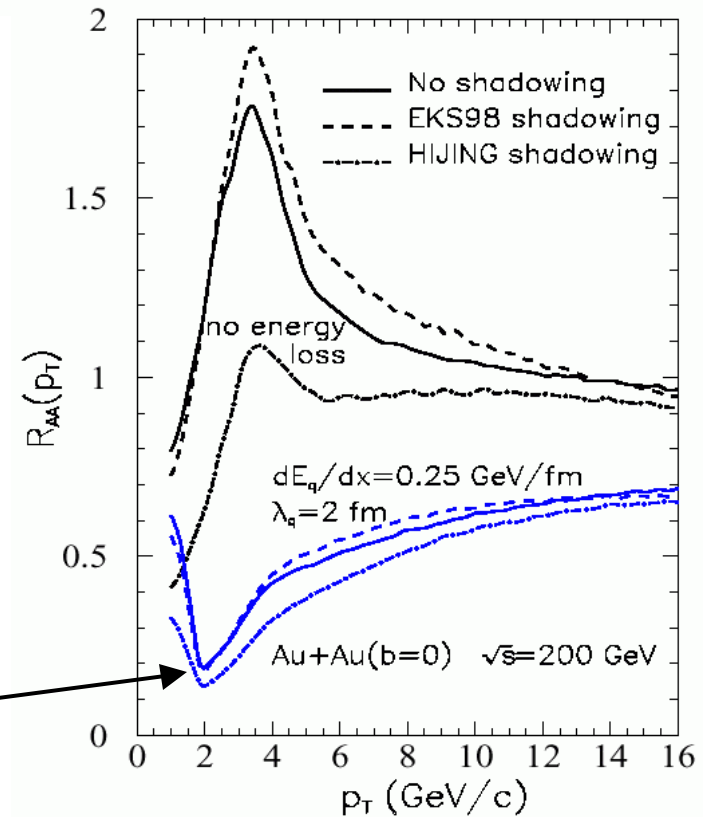
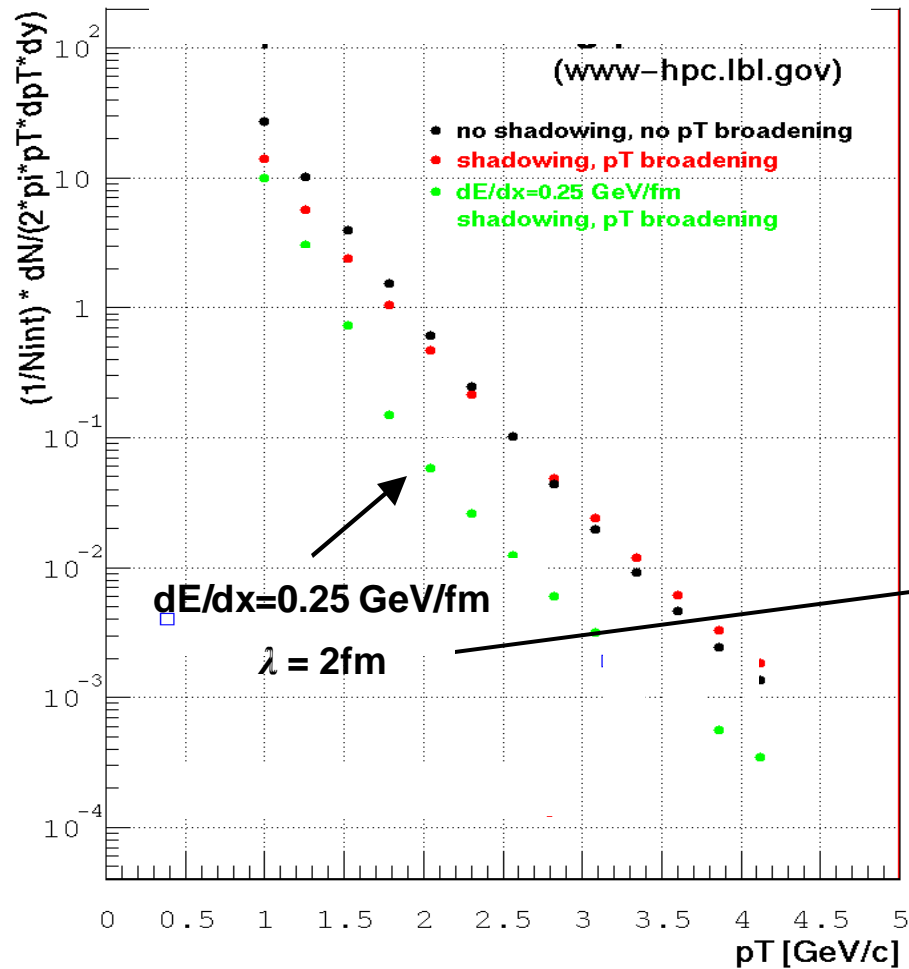
Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267  
 Gyulassy, Levai, Vitev, hep-pl/9907461  
 Wang, nucl-th/9812021  
 and many more.....

The **leading particle** energy is lowered (jet quenching).  
 Hadrons above  $P_t > 1$  GeV are expected to be from jet fragmentation.  
 Thus, we should look for **a suppression of high  $P_t$  hadron production**.

# Some expectations – (predictions!)

X.-N Wang

Neutral pion  $p_T$  – 10% central



Normalize to pp cross section

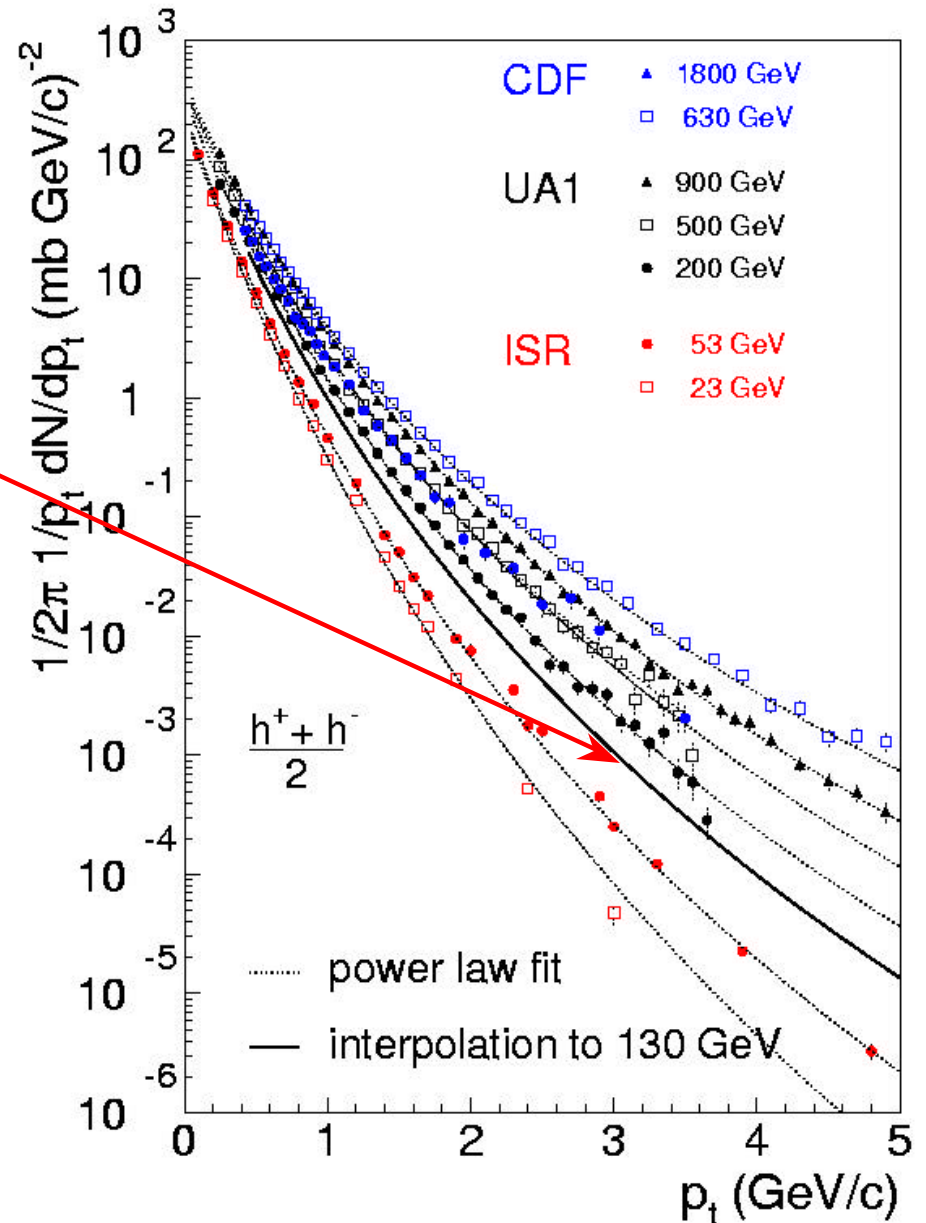
Define:

$$R_{AA} = \frac{1}{\langle N_{bin} \rangle} \frac{AA}{pp}$$

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# Setting the baseline

- To find jet suppression – compare to what?
  - Pp collisions scaled to  $\sqrt{s} = 130$  GeV
    - Good fit to a power law
  - Peripheral collisions – an approximation to pp, or pA and
- Models – Hijing, VNI, etc. + jet  $dE/dx$ 
  - Needed to make quantitative statements about energy loss
  - Some are extensions of standard Monte-Carlo's



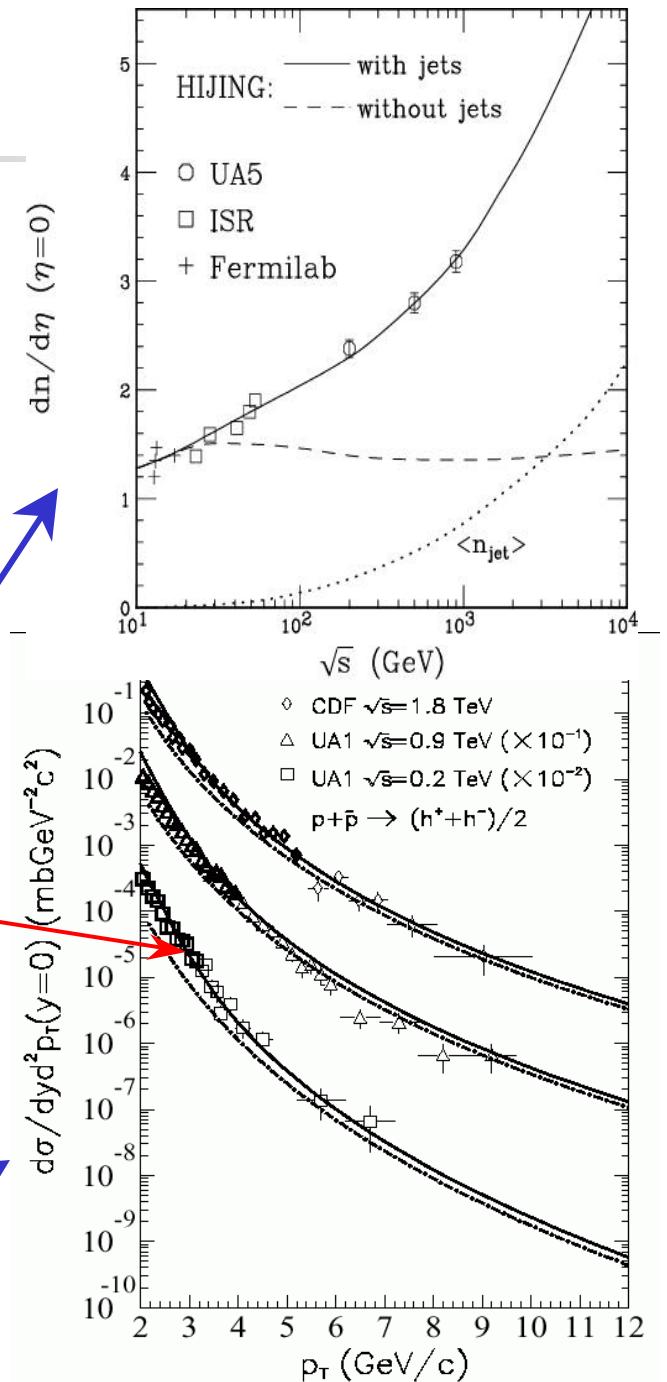
# Models pp, $\bar{p}p$

- Many models of particle production identify two components.
  - Soft interactions where production scales with  $N_{\text{participants}}$ 
    - Strings :  $p < p_0 \sim 1\text{-}2 \text{ GeV}$
  - Hard interactions where production scales with  $N_{\text{binary}}$ 
    - pQCD :  $p > p_0$
    - Initial  $k_T$  included

$$dN_{ch}/d\mathbf{h}|_{h=0} = A \times N_{part} + B \times N_{bin}$$

$$\mathbf{s}_{jet} = \int_{p_T > p_0} dp_T^2 dy_1 dy_2 \frac{1}{2} \sum_{a,b} x_1 f_a(x_1) x_2 f_b(x_2) \frac{d\mathbf{s}_{ab}}{d\hat{t}}$$

$$\mathbf{s}_{qq}(s) = \mathbf{s}_{jet}(s) + \mathbf{s}_{soft}(s)$$



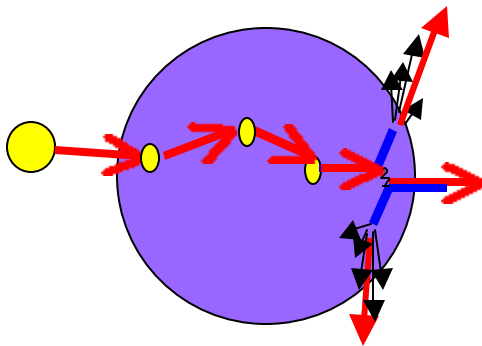
# pp to pA: the Cronin Effect

- Prior parton scattering broadens the transverse momentum spectrum ("Cronin effect"). This has the opposite effect of "Jet Quenching."

- i.e. it enhances high  $p_t$

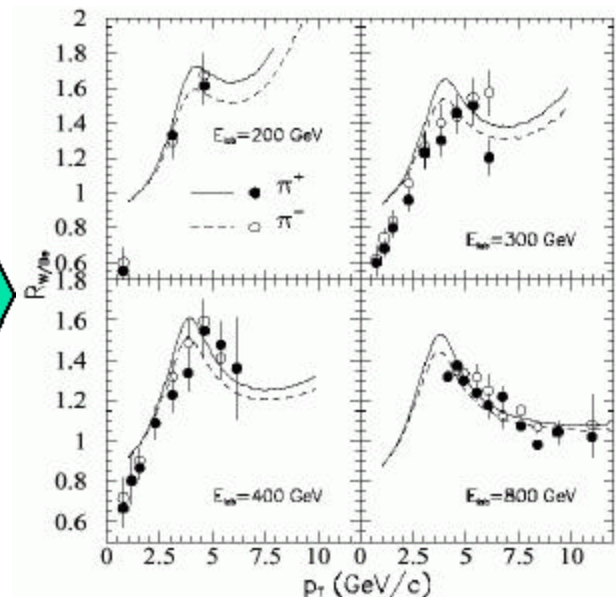
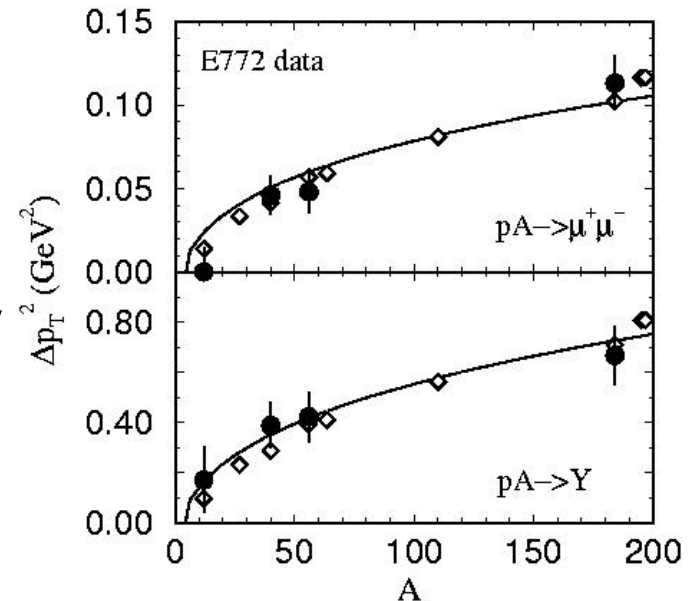
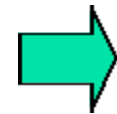
$$\langle p_t^2 \rangle_A = \langle p_t^2 \rangle_{pp} + (A-1) \Delta p_t^2$$

- Not expected to be a large effect at RHIC energies. Big effect at CERN-SPS energies.



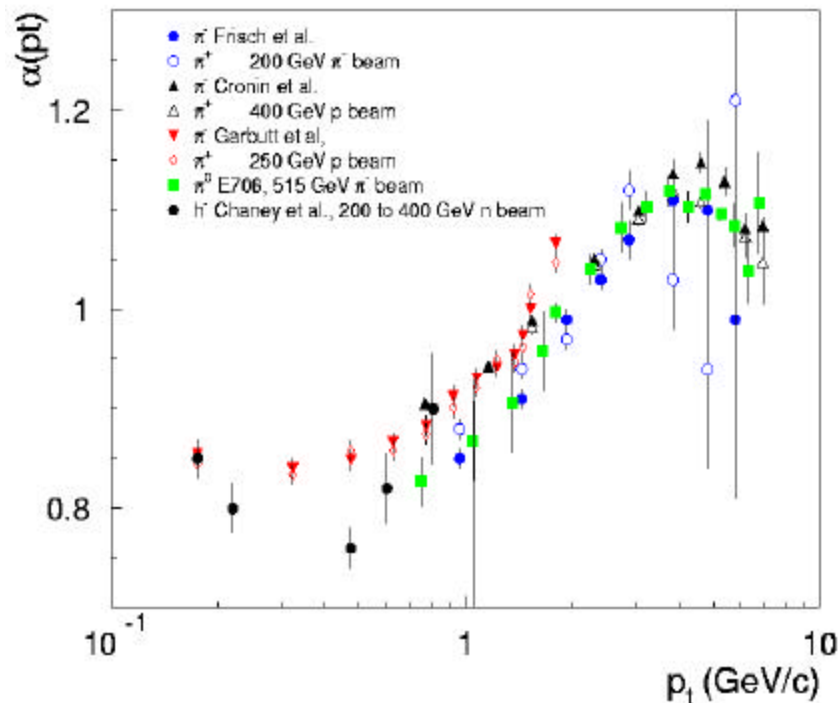
Hijing MC

$$R_{W/Be} = \frac{1}{A_W} \frac{pW}{pBe}$$



# The Cronin Effect

$$\mathbf{s}_{pp} = A^{a(p_t)} \mathbf{s}_{pA}$$

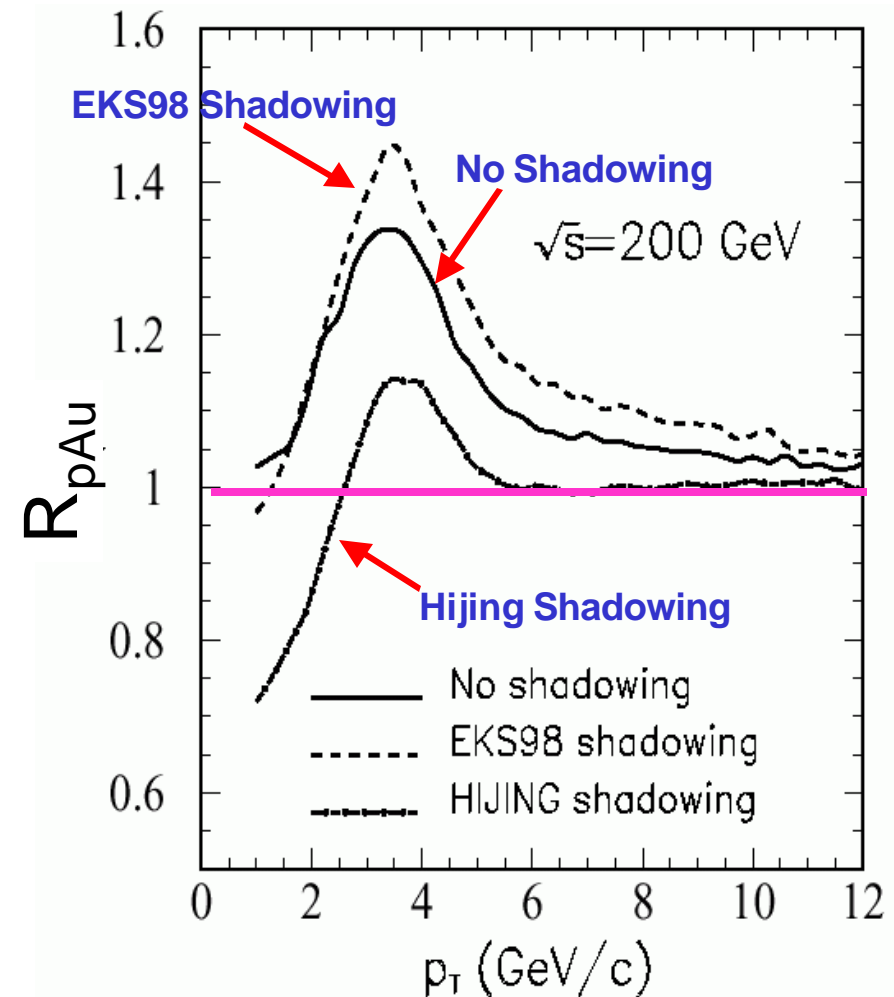


- modification of  $p_t$  spectrum in p-A collisions
- ratio analysis:
- for p-Au collisions
  - increases above 1 at  $\sim 2$  GeV
  - saturates at  $\sim 2$  GeV
  - eventually decreases to 1 at high  $p_t$

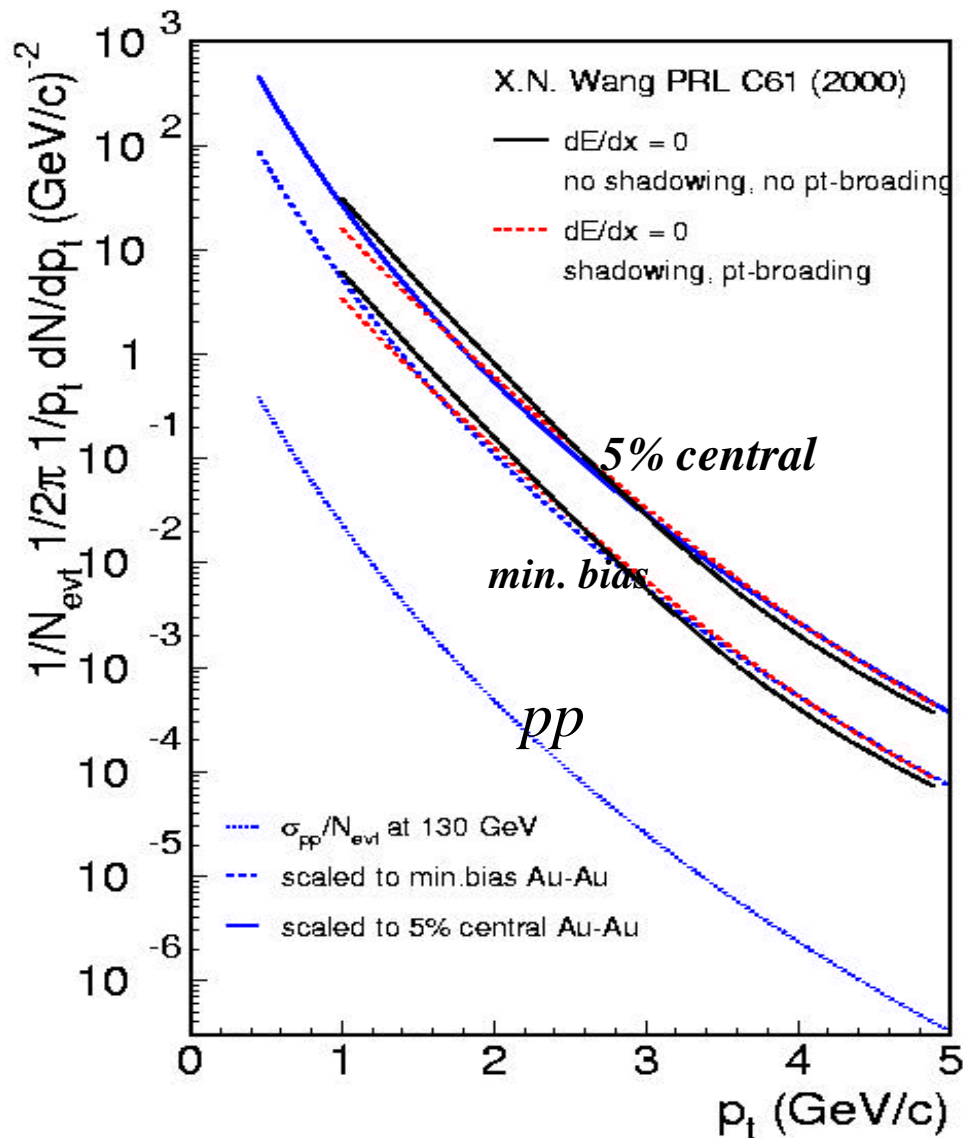
$$R_{pA} = \frac{1}{A} \left( \frac{d^2 \mathbf{s}_{pA}}{dp_t^2} \right) \bigg/ \left( \frac{d^2 \mathbf{s}_{pp}}{dp_t^2} \right)$$

# pp to pA: Nuclear shadowing

- Nucleon structure functions are known to be modified in nuclei. Fewer partons than otherwise expected will lead to fewer high  $P_t$  particles.
- **Gluon shadowing**
  - is not measured,
  - large role at RHIC
- Measure pA at RHIC!
  - For now depend on peripheral events



# pp to AA: Nuclear Geometry



$$T_A(b) = \int dz \mathbf{r}_A(z, b)$$

## Glauber Eikonal Geometry

$$T_{AB}(b) = \int d^2s T_A(s + \frac{b}{2}) T_B(s - \frac{b}{2})$$

- Hard processes scale with binary collisions
  - scaling to min. bias Au-Au:

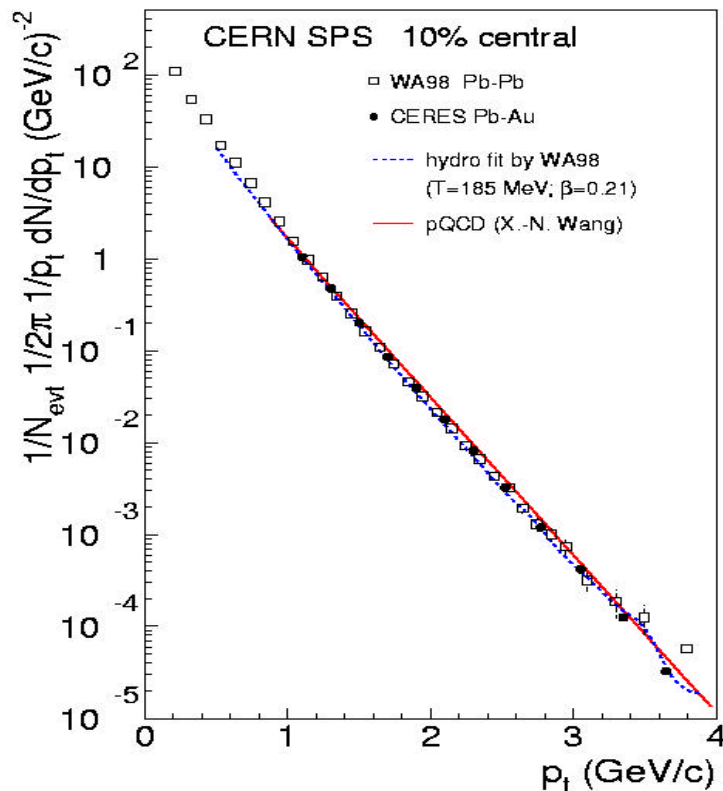
$$s_{AA}(b < b_c) = s_{pp} \int_0^{b_c} d^2b T_{AA}(b)$$

- scaling to central collisions:

$$s_{AA} = A^2 s_{pp}$$

$$T_{AA}(b \ll R) \approx \frac{A^2}{pR^2} \approx \frac{A^{4/3}}{s_{pp}}$$

# Results from the SPS



- data well described by pQCD
  - (intrinsic + initial)  $k_T$  (A,Q) broadening
- data equally well described by hydrodynamic fit

# Comparing CERN-SPS Pb-Pb to p-p

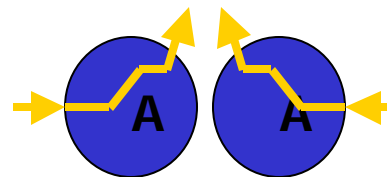
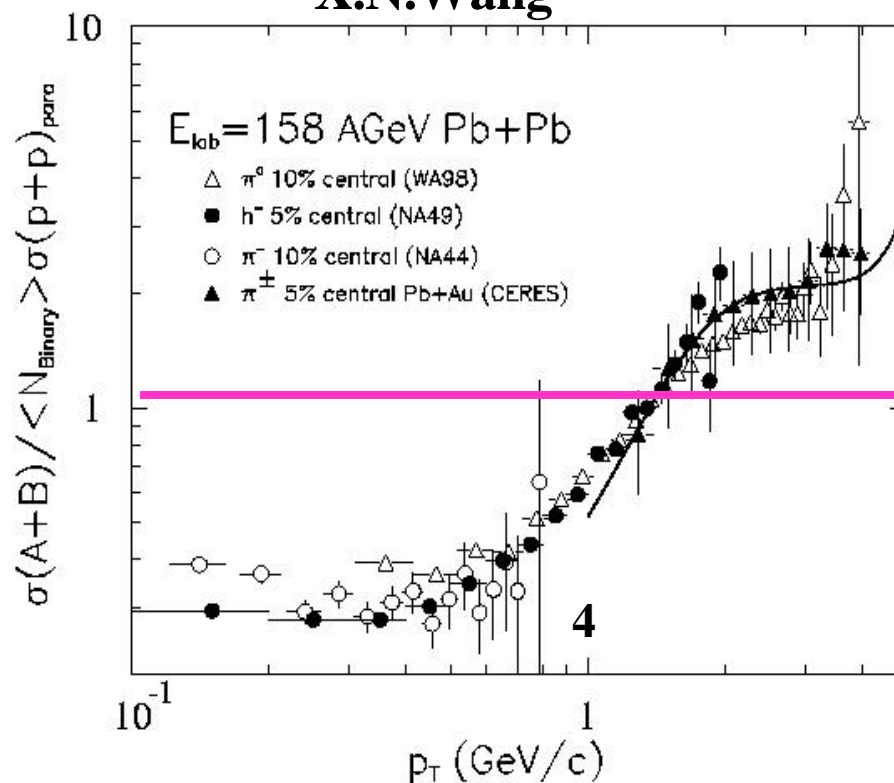
X.N.Wang

- $R_{AA}$  exhibits amplified Cronin Enhancement at SPS energies

$$R_{AA} \gg (R_{pA})^2$$

- Parton energy loss, *if any*, is overwhelmed by initial state soft multiple collisions at SPS!

$$R_{AA} = \frac{1}{\langle N_{bin} \rangle} \frac{AA}{pp}$$

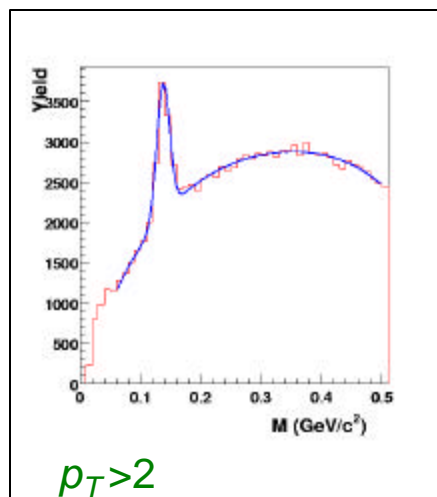
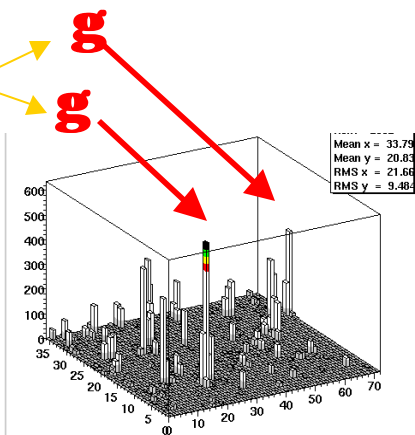
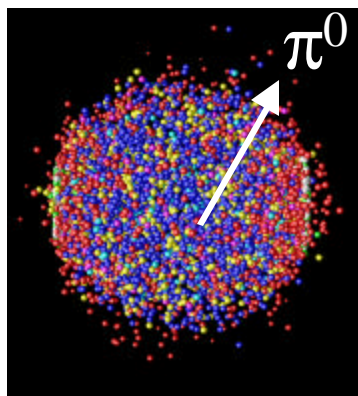


\*  $dE/dx$  is small at SPS due to short plasma lifetime and low gluon density

MG, P. Levai, I. Vitev, PRL85(00)5535

Richard Seto

# $\pi^0$ spectra



$p_T > 2$   
GeV, asym < 0.8

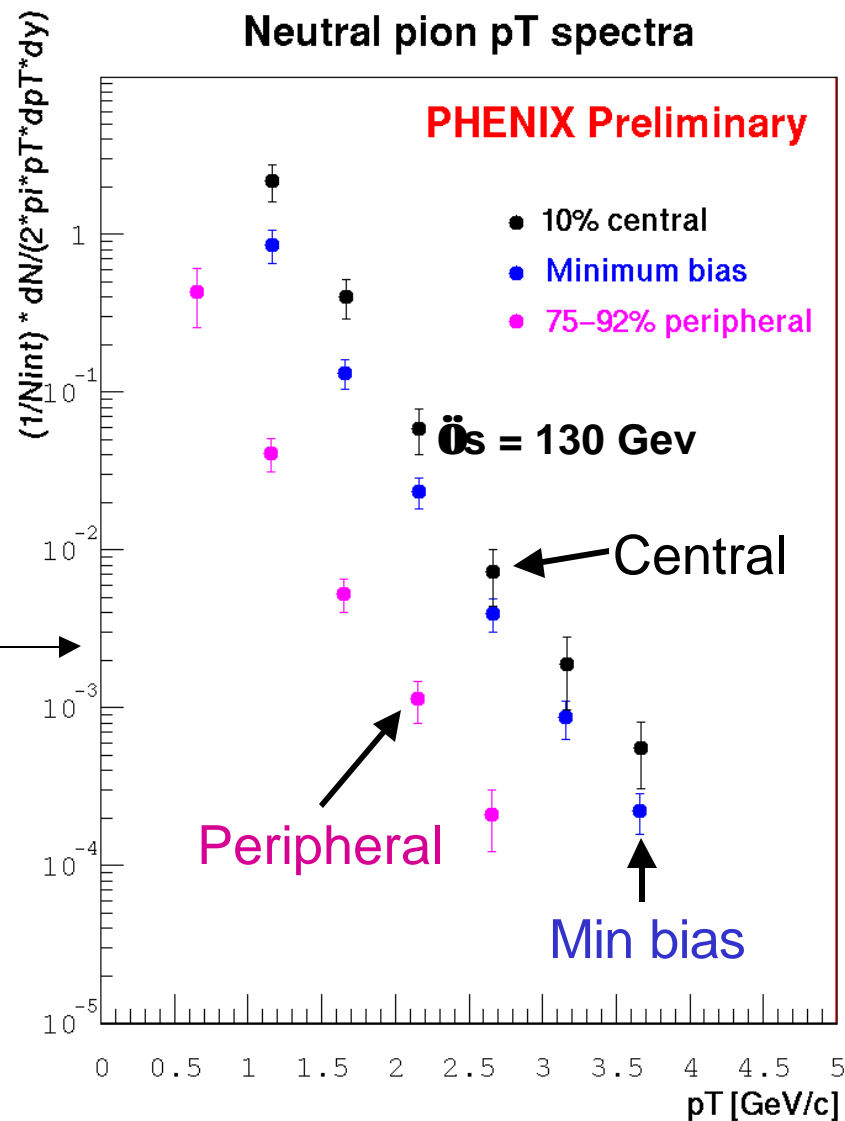
*Systematic errors included*

*Main sources:*

- *peak extraction*
- *PID loss*
- *efficiency calculations*
- *non-vertex pions*
- *$p_T$  scale*

## Neutral pion $p_T$ spectra

**PHENIX Preliminary**

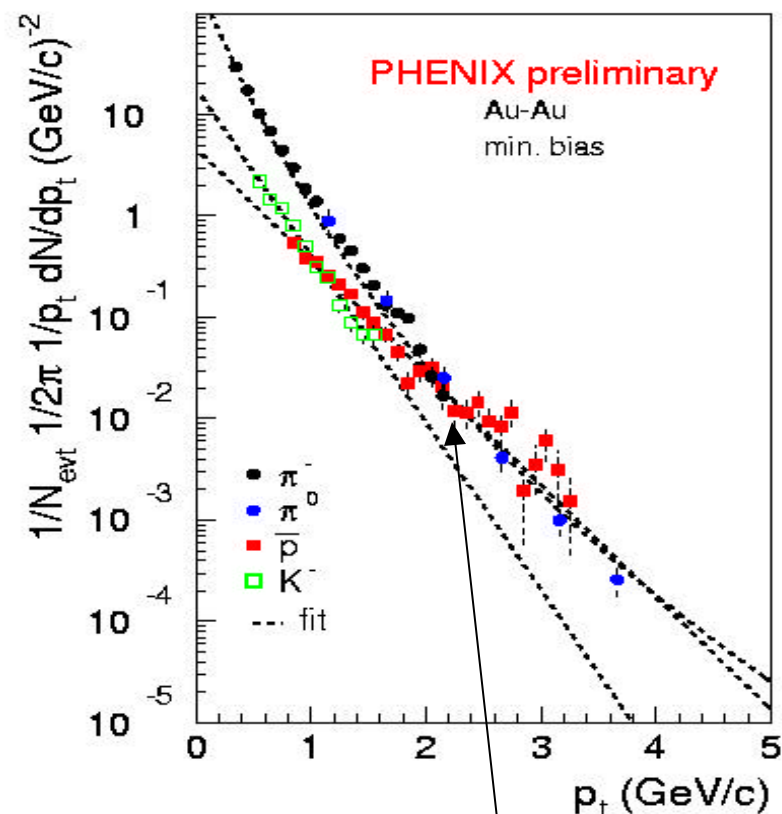
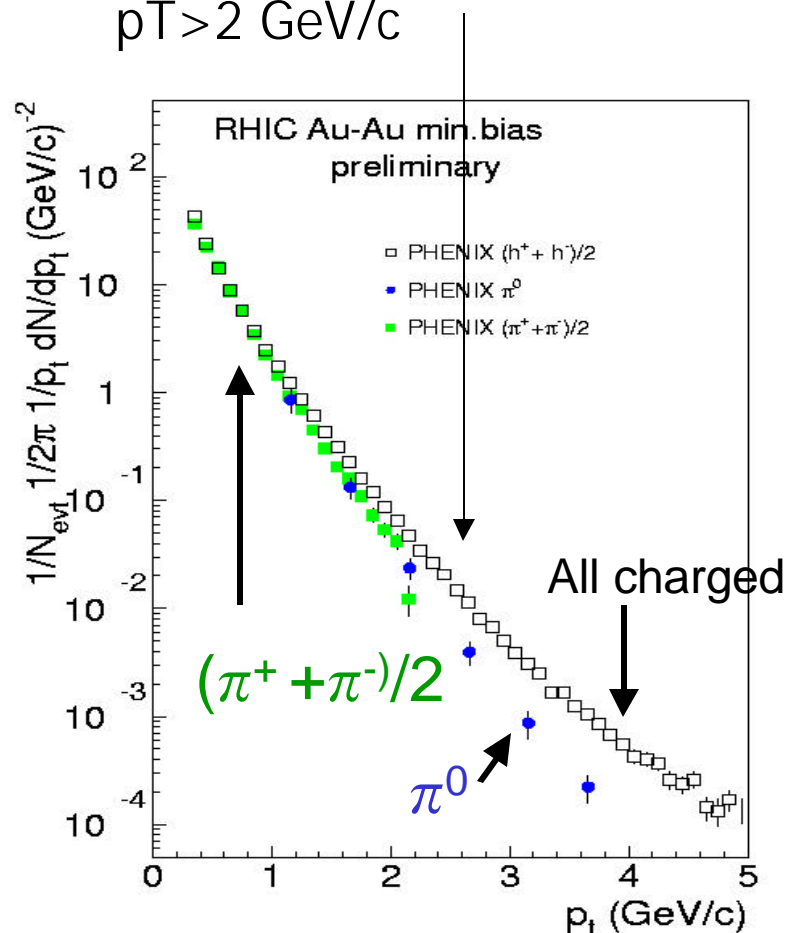


~1M Min Bias AuAu events

Richard Seto

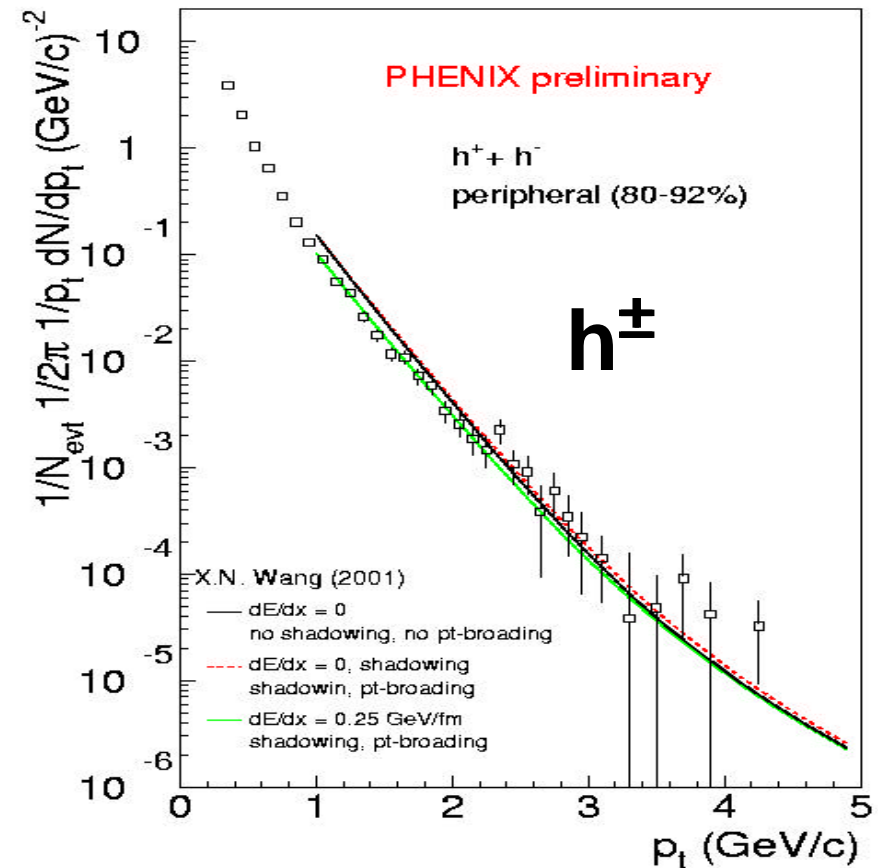
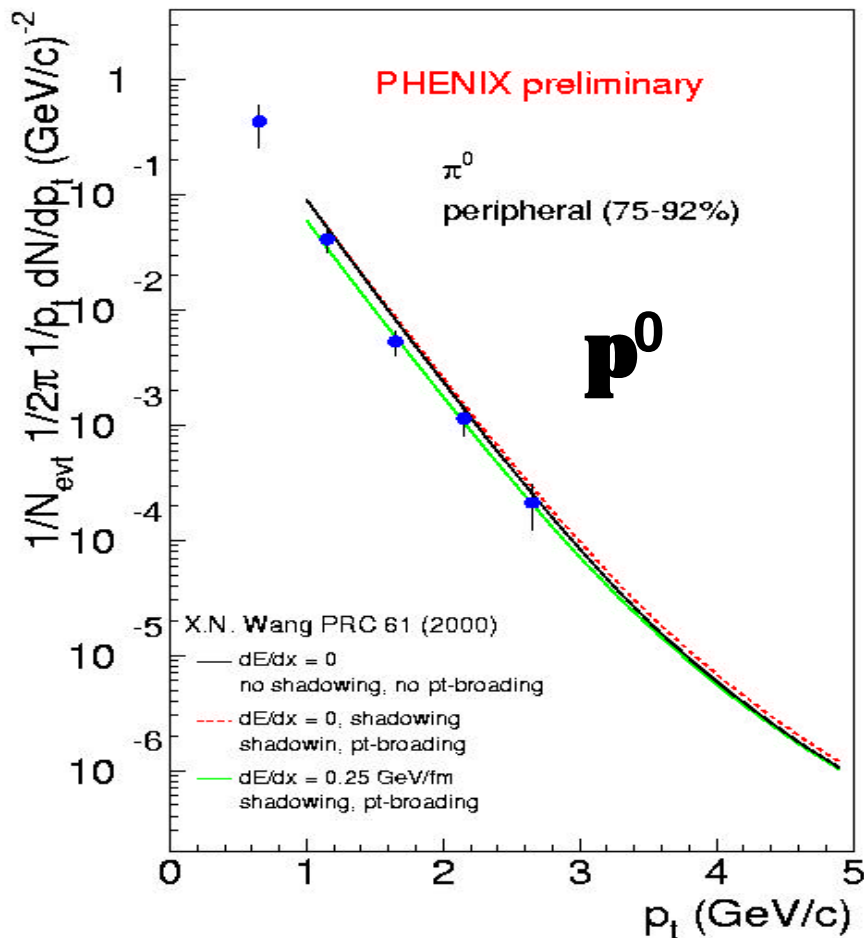
# Comparison to charged spectra

- $\pi^0$  spectra matches charged pion spectra – different systematics!
- Charged spectra has an excess for  $p_T > 2$  GeV/c



- PID'ed spectra:  $p \geq \pi^-$  for  $p_T > 2$  GeV/c
- Charged spectra matches well to  $\pi + K + p$

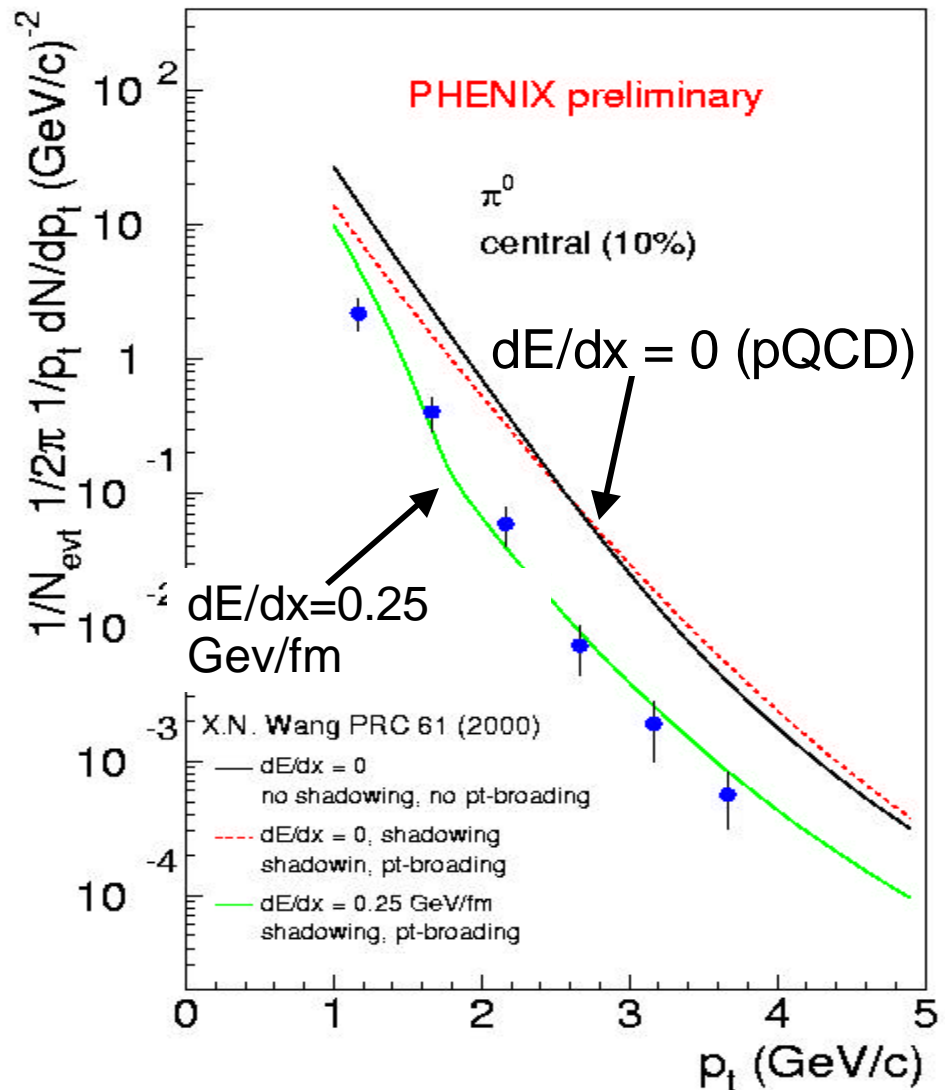
# Comparison with QCD calculations: Peripheral Events



- good agreement with pQCD calculation in Peripheral Collisions
  - Includes Intrinsic  $k_T$ , Cronin, shadowing
- Baseline is OK

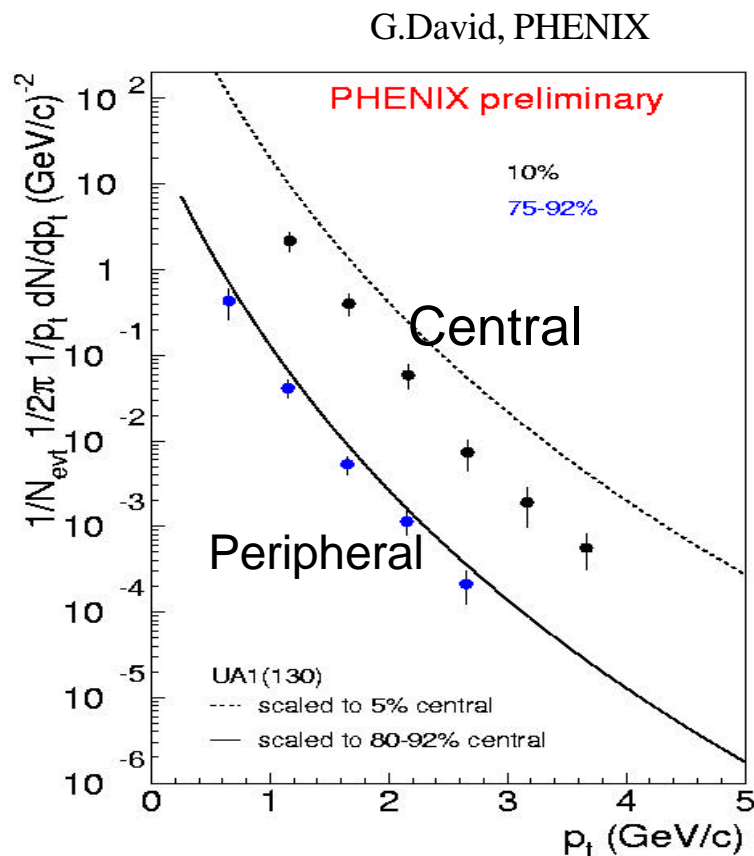
# Central Events – Jet quenching?

- p-QCD over estimates the cross-section
  - for  $\pi^0$  at least  $\sim 5$
- shadowing and  $p_t$ -broadening seem insufficient
- calculation including constant energy loss
  - consistent with  $\pi^0$

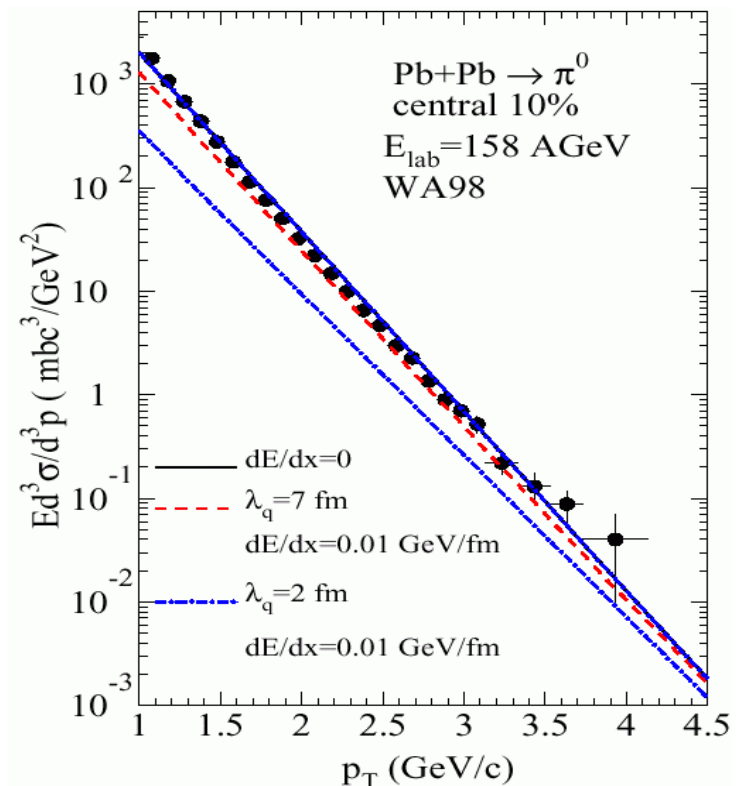


# Some sanity checks

- Just compared to scaled  $\sigma_{pp}$  (UA1 fit 130)
- Still suppression x5



- Maybe scaling is wrong?
- Check with central collisions at the SPS (where we don't see quenching)
- No quench hypothesis fits well to central events

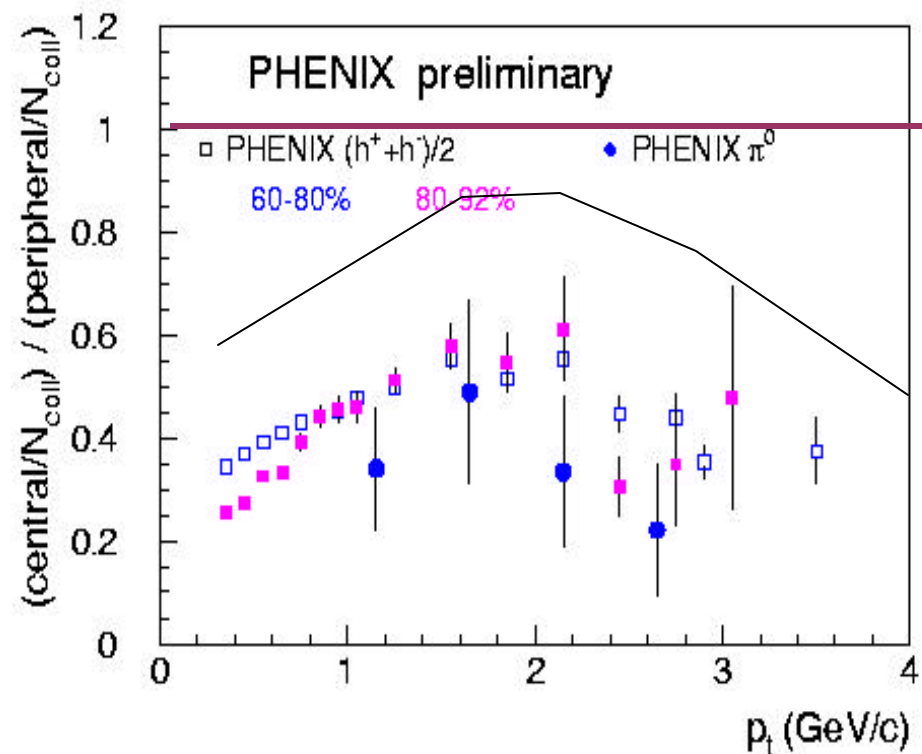


# Ratio Central/Peripheral

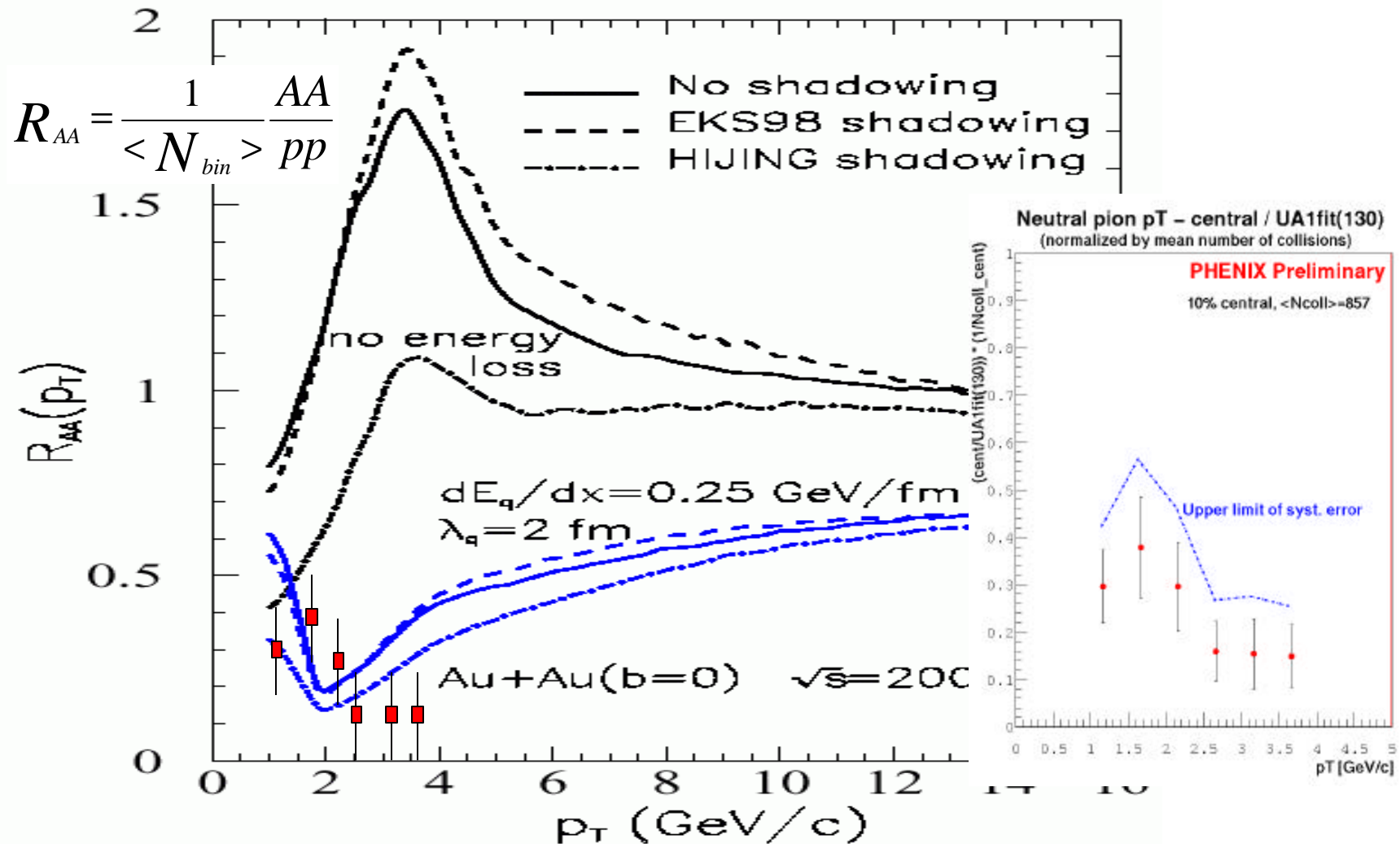
- normalize central to peripheral divided by  $N_{\text{Binary}}$
- different systematic errors:
  - many experimental errors cancel
  - systematic uncertainty  $\sim 60\%$  on  $N_{\text{coll}}$

within systematic errors:

$$R_{AA} < 1$$



Divide by  $\langle N_{\text{binary}} \rangle \sigma_{pp}^{\text{(UA1 fit 130)}}$

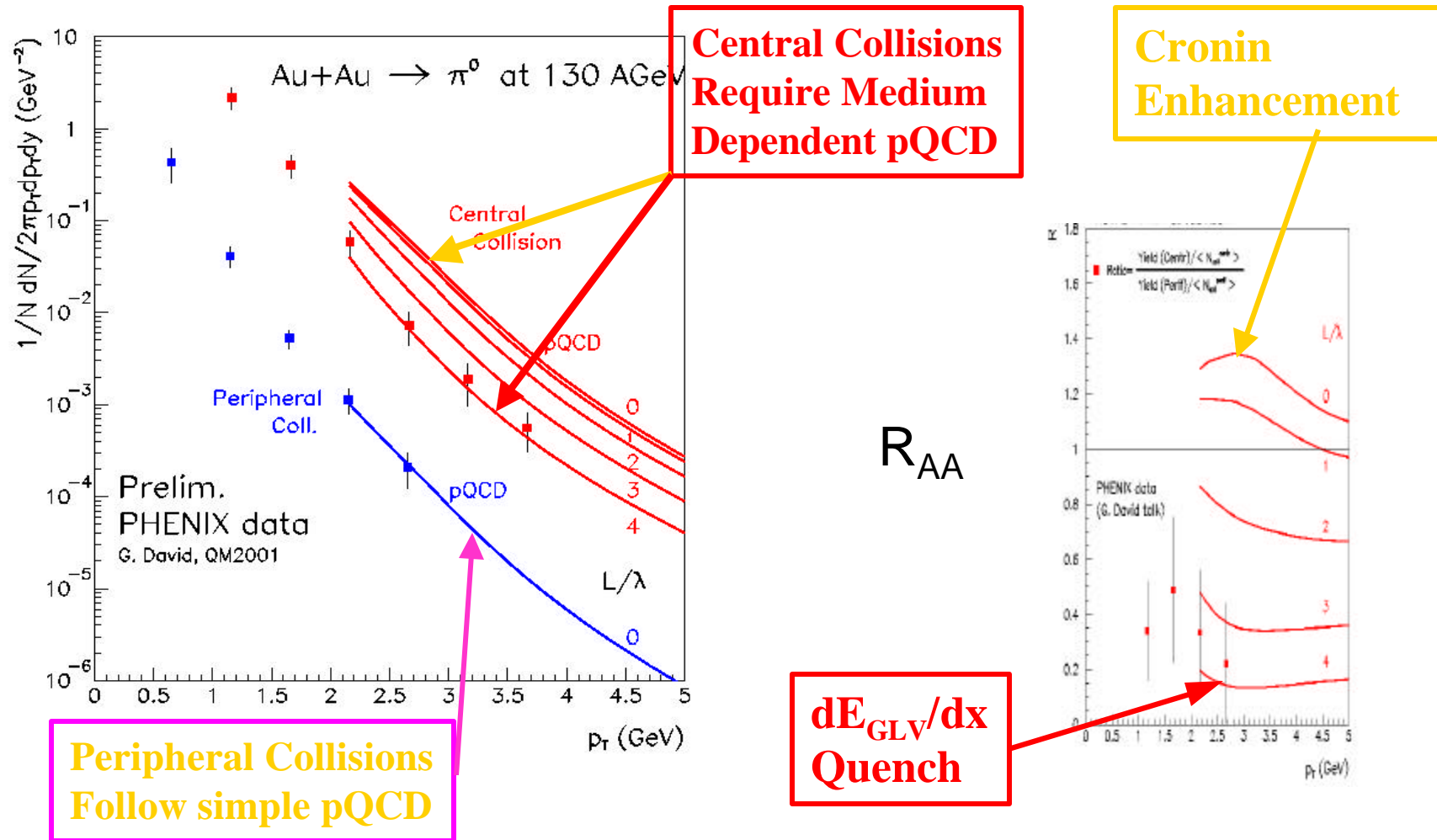


Note 0s for model is 200 GeV

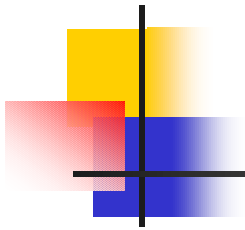
Richard Seto

# Comparison with pQCD

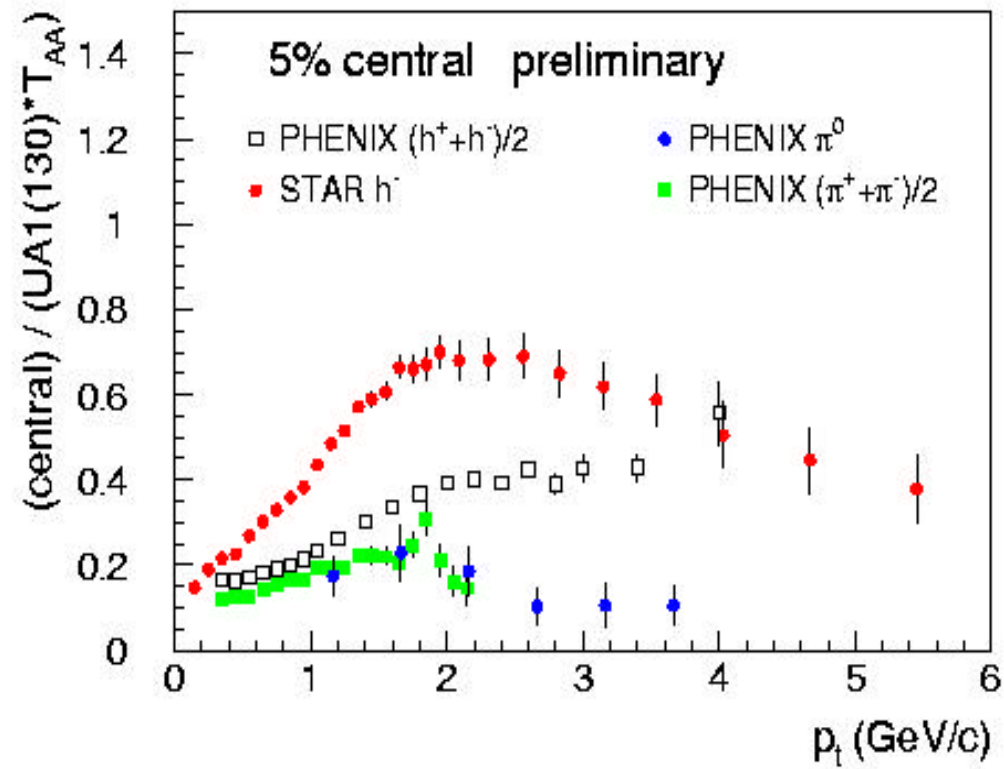
P. Levai, G. Fai, G. Papp, MG (QM01)



Richard Seto



Spare

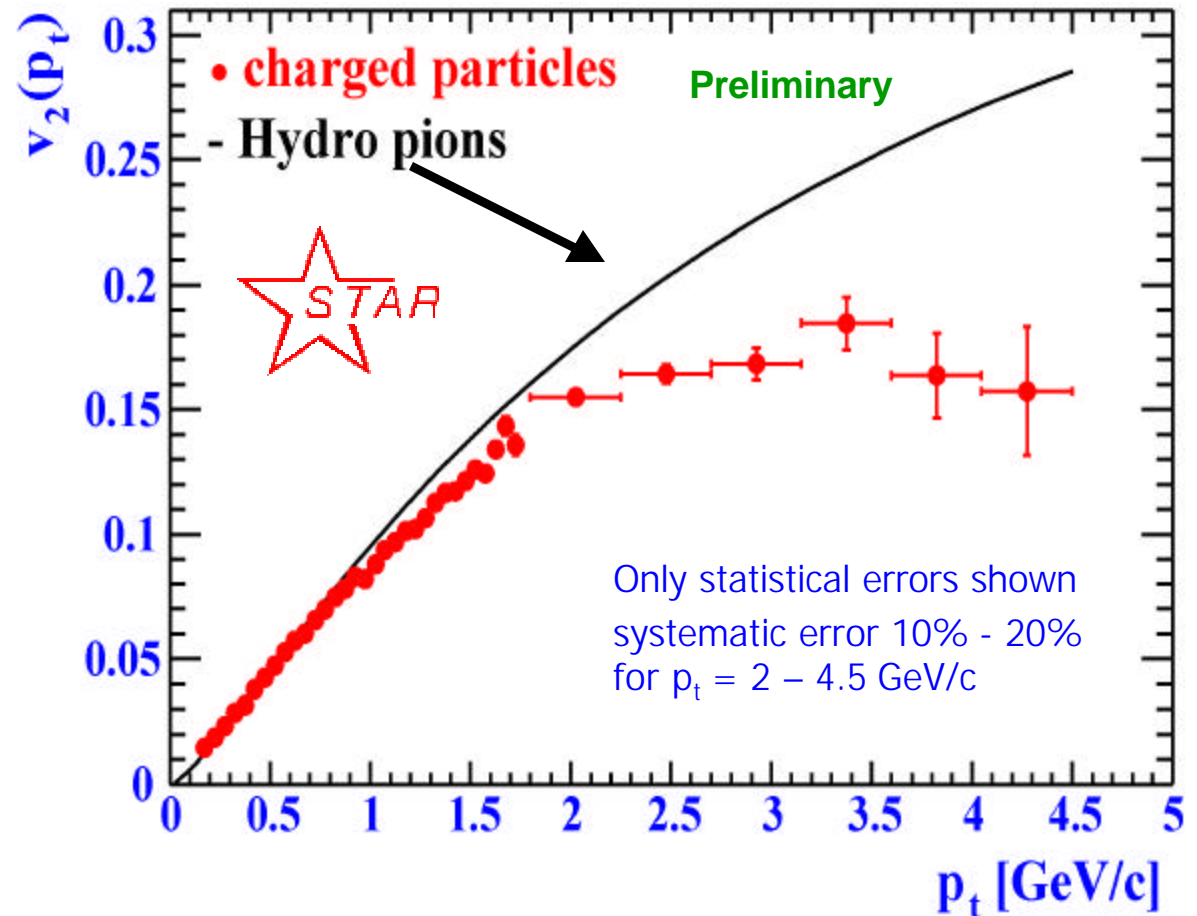


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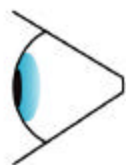
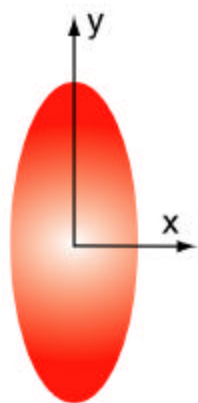
# Charged particle anisotropy

## $p_t < 4.5$ GeV/c vs Hydrodynamics

- Hydrodynamics seems to overpredict  $v_2$  for  $p_T > 2$  GeV
- If high  $p_T$  particles come from hard scattering, you would not expect them to be in equilibrium hence hydrodynamics won't work
- Jet quenching for non-Central events?
- Caveat – comparing to all charged

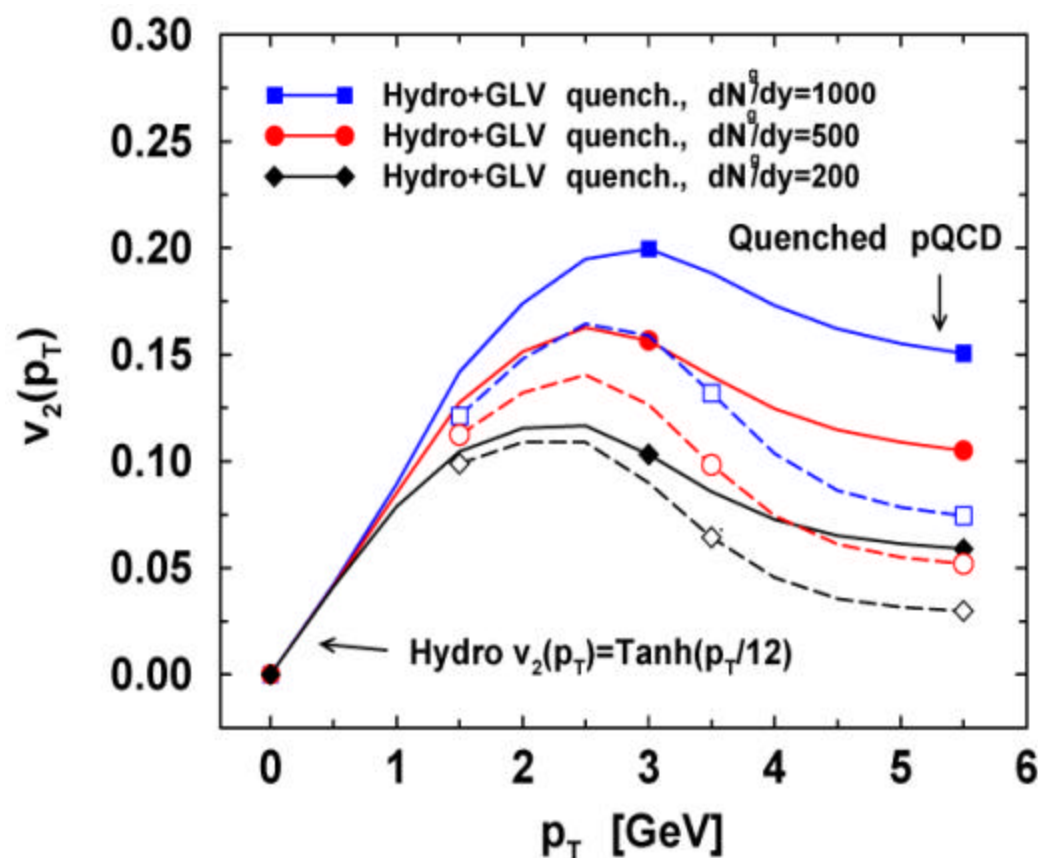
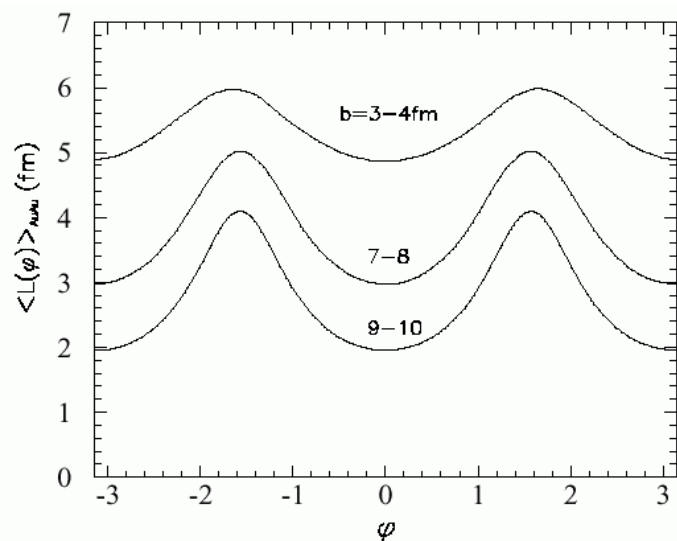


# $v_2(p_t)$ for high $p_t$ particles Hydro + quench model



Gyullasy, Vitev, Wang combine a hydrodynamic model with a jet quenching scenario.

$$dE/dx \sim L$$

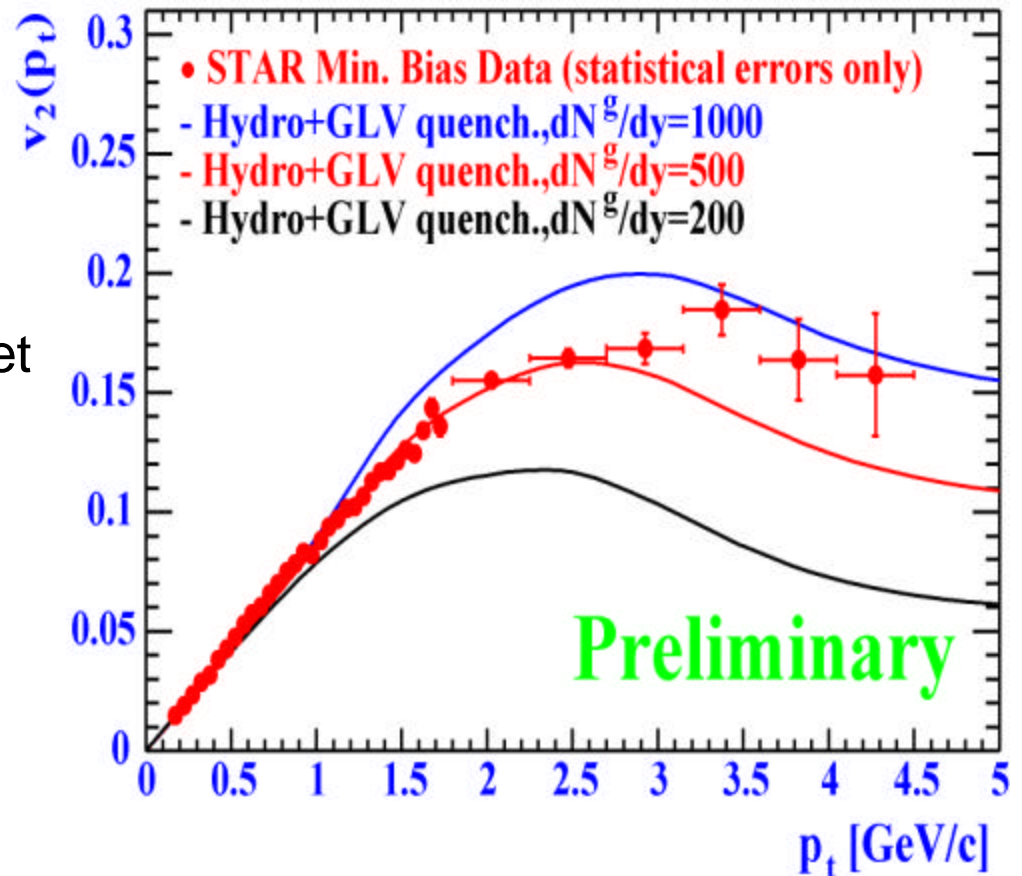


MG, I. Vitev and X.N. Wang, nucl-th/00012092

Richard Seto

# Preliminary STAR Charged particle anisotropy

- Differential  $v_2(p_T)$ :
  - Hydro up to  $\sim 1.5$  GeV
  - Flow signal consistent with Jet Quenching!
- Constraint on Initial Conditions:
  - $dN_{\text{glue}}/dy > 500$



system. error 10% - 20% for  $p_T = 2 - 4.5$  GeV/

**Flow signal consistent with Jet Quenching!**

Kolb et al (Hydro) + MG, P. Levai, I. Vitev ( $dE_{\text{QCD}}/dx$ ) PRL85(00)5535

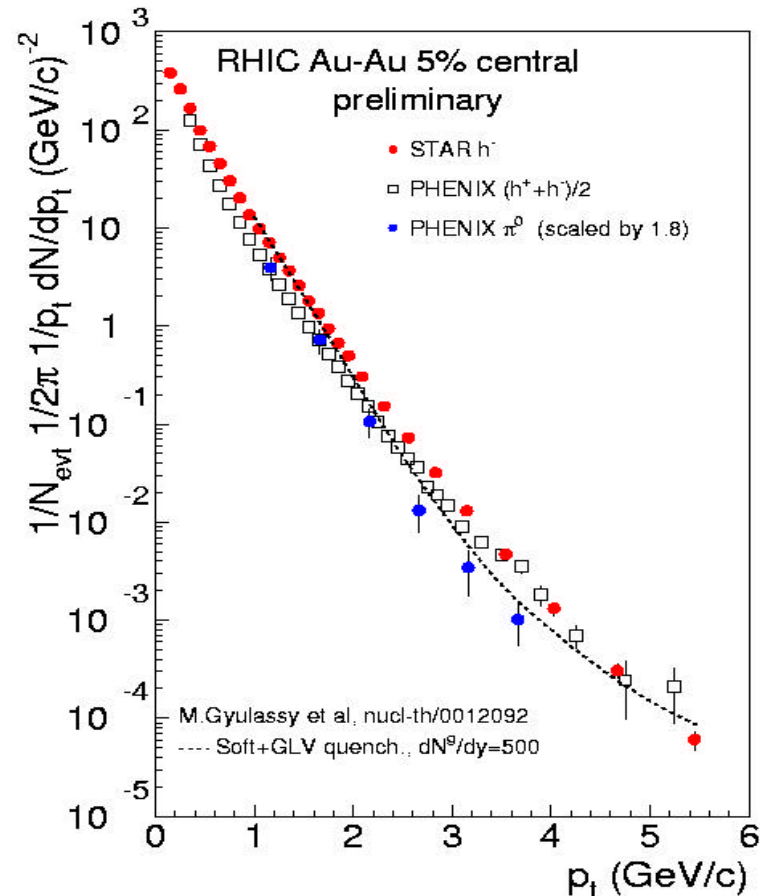
MG, I. Vitev and X.N. Wang, nucl-th/00012092, PRL in press

Richard Seto

# Comparison with $p_t$ distribution

Hydro+GLV: M. Gyulassy, I. Vitev  
and X.N. Wang, nucl-th/00012092

- calculation compatible with
  - anisotropy measurement
  - and  $p_t$  - spectra

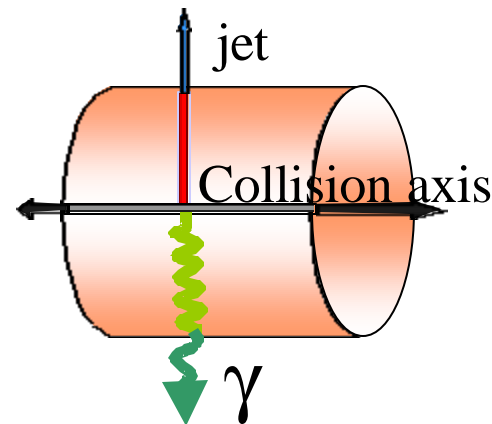


# Jets : the future

- Next run (starting in May 2001)
  - p0 to Pt ~ 10 GeV !
    - Greater sensitivity to exact energy loss
      - How big?
      - Proportional to mean free path?
  - Back to back high pt particles
  - pA running??? Critical !
  - Possibly high pt K-
    - Has no valence quarks – should be sensitive to gluon jets
      - Gluons should have more higher dE/dx than quarks

- Later as Luminosity increases

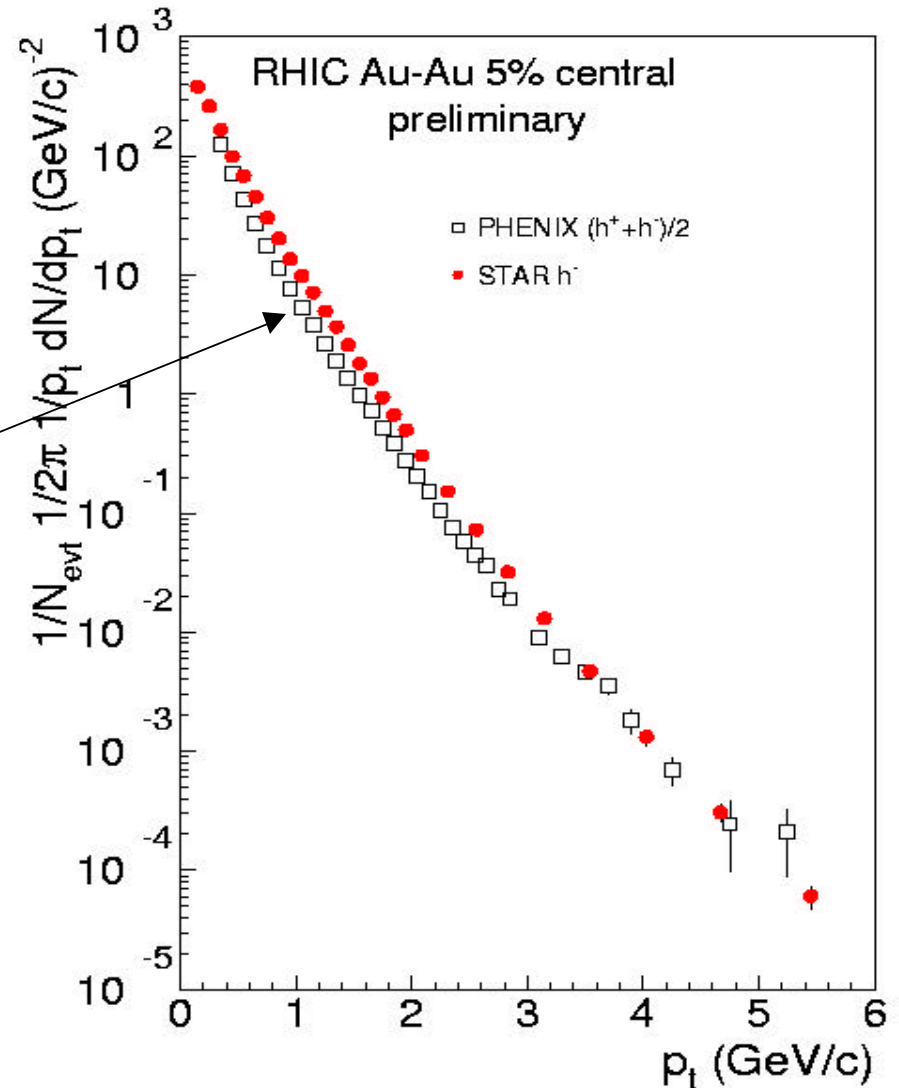
- Direct  $\gamma$ -tagged events:  
 $E_g \sim E_{\text{jet}}$



# Some Dirty Laundry

J.C. Dunlop, STAR  
F. Messer, PHENIX

- Comparison of charged particle spectra from
  - PHENIX  $(h^+ + h^-)/2$
  - STAR  $h^-$
  - 30% discrepancy
  - Careful comparisons between experiments with the same cuts have yet to be made

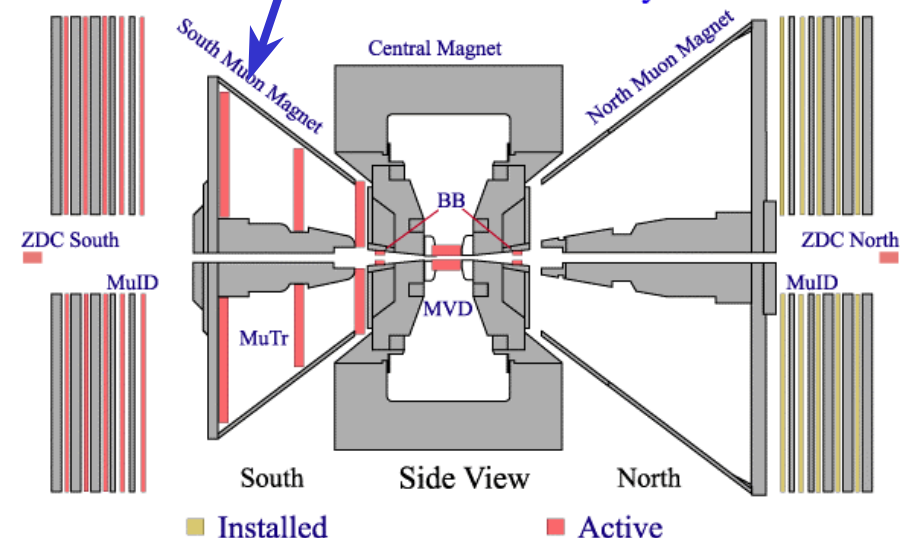


# Shape of Things to Come

- Completion of Central Arms
    - Significantly increased aperture
      - ➔ *Electrons!*
  - Addition of new capabilities
    - South Muon Arm
      - ➔ *Di-muon physics*
  - Upgraded
    - Triggers
    - Data Acquisition
- ➔ The ~5M events recorded in Run-1 represent ~1 day of data-taking for RHIC+PHENIX in Run-2



PHENIX Detector - Second Year Physics Run



# Vector Meson mass shifts in the dilepton channel

## Chiral symmetry restoration

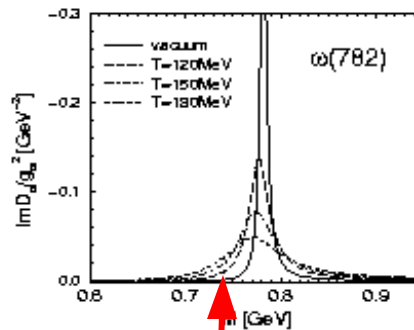
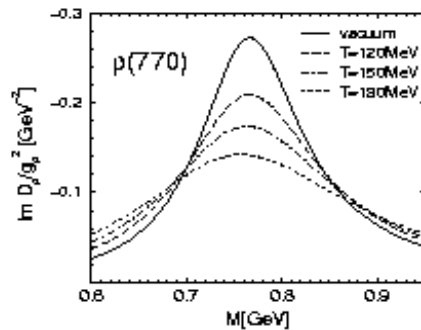
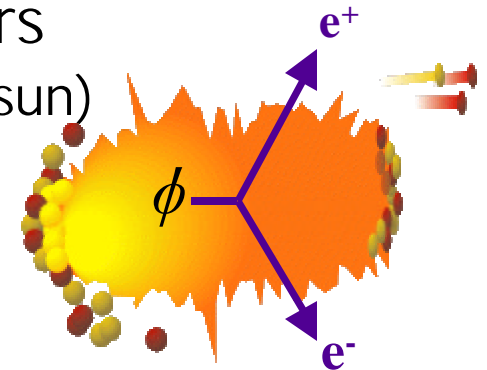
- “Light” Vector mesons are ideal probes ( $\rho, \omega, \phi$ )

- Like putting a scale to measure mass inside the fireball
- Short lifetime  $\sim$  few fm/c
- ➔ Decay inside hot fireball



- Electrons (and muons) are ideal messengers

- Don't interact strongly (e.g. neutrinos from the sun)



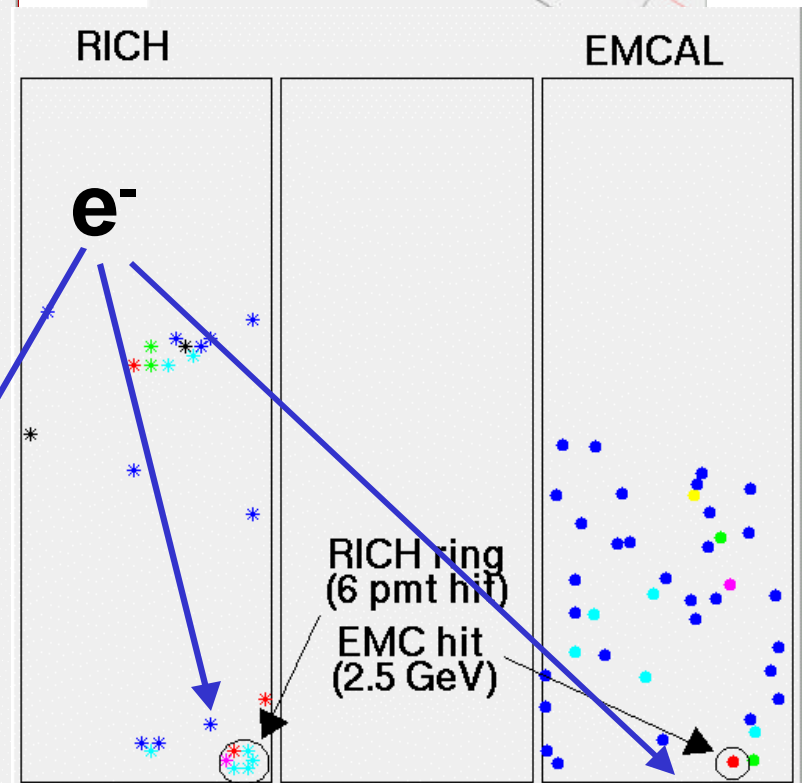
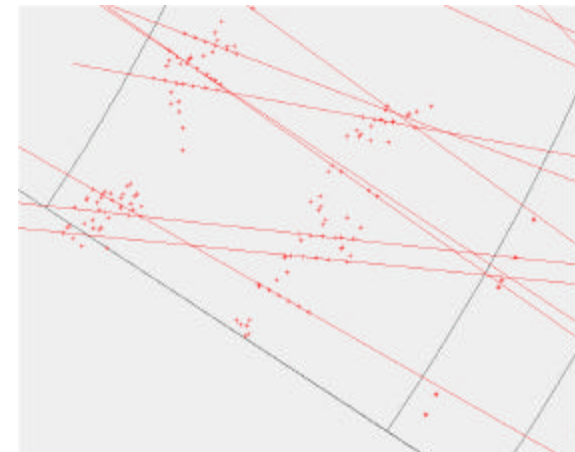
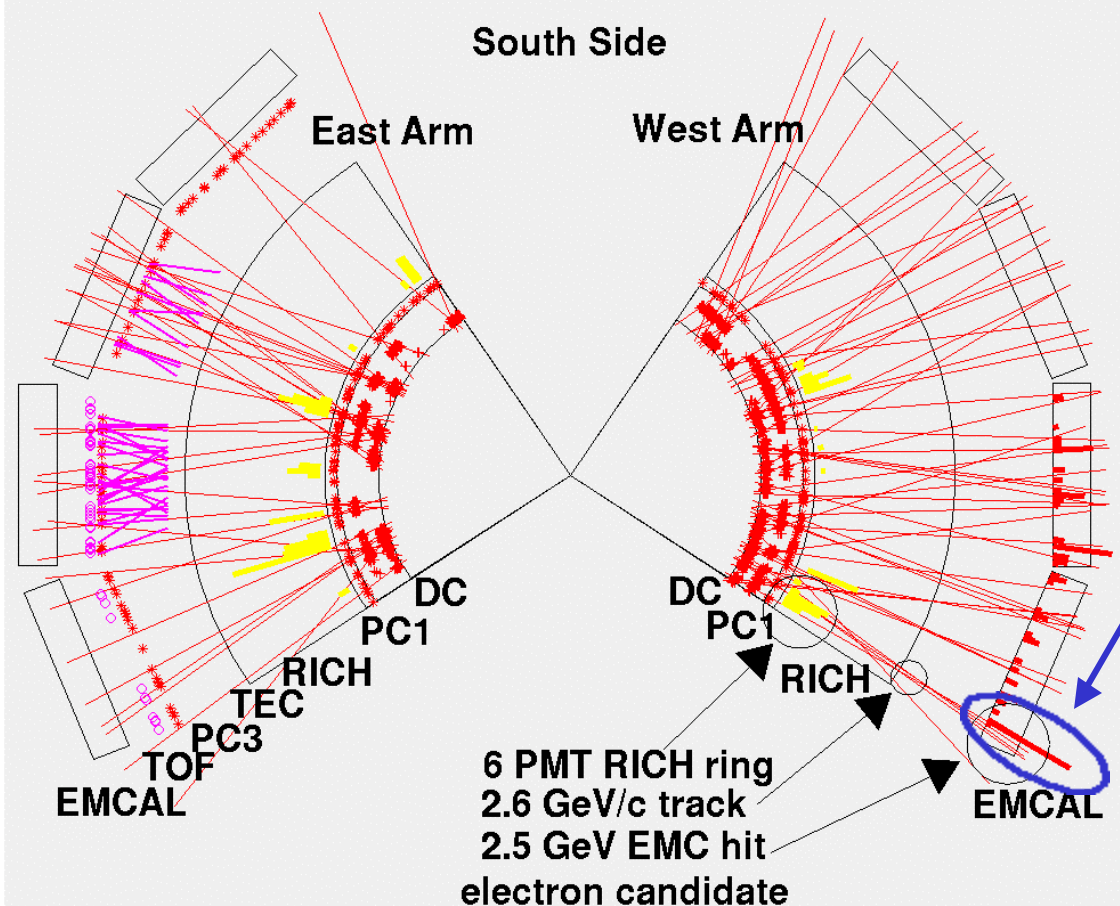
- In Medium  $\rho, \omega$

- R. Rapp (Nucl. Phys A661(1999) 238c
- ♦ shows low mass tail -
  - With its good mass resolution PHENIX should be able to see this

# All sub-systems in concert

## High $p_T$ electrons in PHENIX:

PHENIX RUN 12010 seq0010 event 291



# Color Screening in a Deconfined Media- J/ $\psi$ suppression

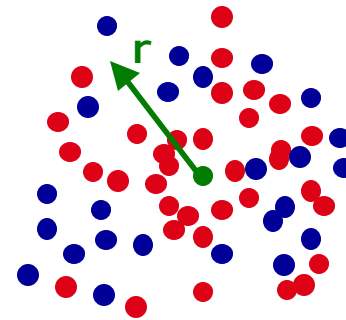
## ■ Debye Screening

- In a deconfined media a test quark  $q$  polarizes the surrounding media
- The color screening suppresses the long range confining part of the strong interaction.

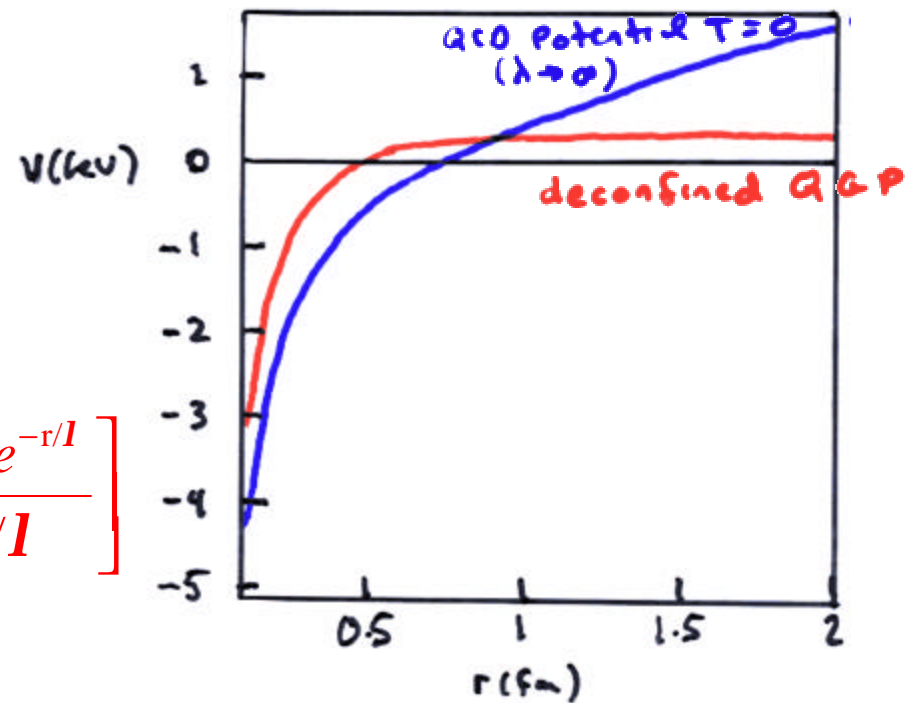
Satz , Matsui PL178B(1986)416

$$V(r) = -\frac{a}{r} + kr \xrightarrow{\text{confinement}} -\frac{a}{r} e^{-r/l} + kr \left[ \frac{1 - e^{-r/l}}{r/l} \right]$$

↑ "coulomb"      ↑ confinement



- Test quark placed at  $r=0$
- quarks
- Anti-quarks

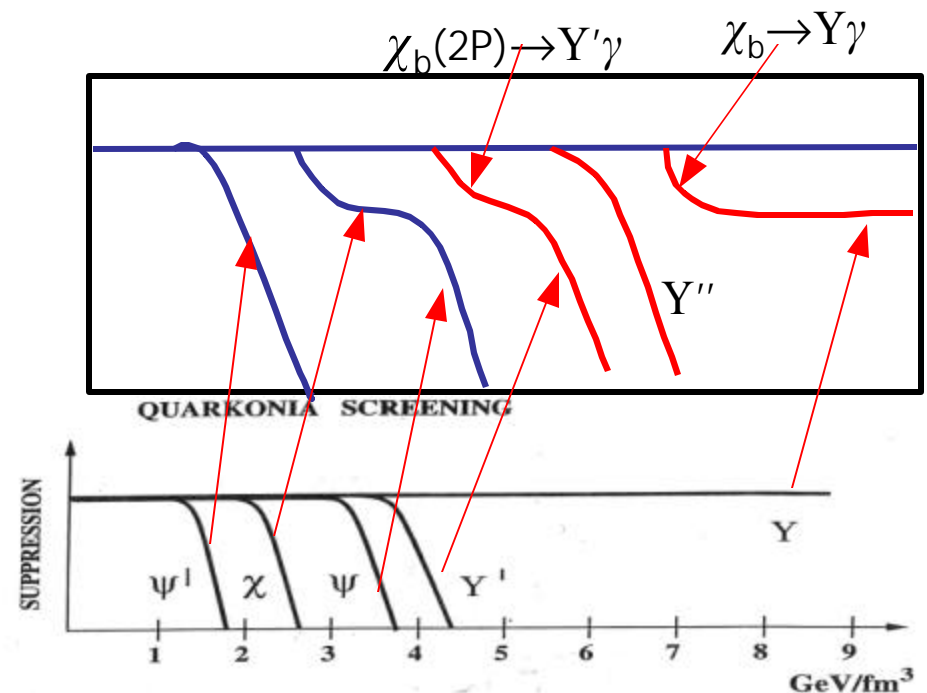


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# Onium Suppression $J/\psi$ and $\Upsilon$

## Muons and electrons

- RHIC (for a robust result)
  - Onium system as thermometer
  - Rates (no anomalous suppression)
    - $J/\psi$  Au-Au  $0.4 \times 10^6/\text{yr}$
    - $\Upsilon + \Upsilon' + \Upsilon''$  1000 events 30 weeks
  - Also need  $p_T$  Dependence
  - Study vs sytem size and energy





# Other topics

---

- STAR will add
  - Silicon Vertex Tracker
    - Measurement of  $\Xi$   $\Omega$
  - large acceptance EMCAL over the next several year
    - Will get into the electron and photon game
- Other Physics Topics – all detectors
  - Heavy quarks
  - pA physics
  - Of course spin physics



# Conclusions

---

- Energy density  $\sim 1.5 \times$  value at CERN SPS
- Observation of significant elliptic flow indicating thermalization
- Systematic study of  $p_T$  spectra for
  - $\pi^0$ 's
  - Charged particles

versus centrality show

- Good agreement for peripheral collisions with predictions from hard scattering
- Clear deficit in more central collisions
  - Data-to-data comparisons
  - Data-to-model comparisons

**high- $p_t$  data are consistent with “jet quenching” predictions !**

- *Ideally positioned to dramatically extend these results in second year of RHIC running*